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DESCRIPTION

METHOD OF ASSUMING ACTING POINT OF FLOOR REACTION FORCE TO BIPED WALKING MOBILE BODY AND METHOD OF ASSUMING JOINT MOMENT OF BIPED WALKING MOBILE BODY

Technical Field

The present invention relates to a method of estimating the position of a floor reaction force acting point of each leg of a biped walking mobile body, such as a human being or a biped walking robot. The present invention further relates to a method of estimating the moment acting on a joint of a leg of a biped walking mobile body by using an estimated value of the position of the floor reaction force acting point.

Background Art

To control an operation of, for example, a walking aid apparatus for assisting a human being in walking or to control a traveling motion of a biped walking robot, it is necessary to successively grasp the floor reaction forces acting on legs of the human being or the biped walking robot (to be more specific, the forces from a floor that act on ground contact portions of the legs) and the positions of floor reaction force acting points. Grasping the floor reaction forces and the floor reaction force acting points makes it possible to grasp moments or the like acting on joints of the legs of the bipedal walking

mobile body, and to decide target auxiliary forces of the walking aid apparatus or desired drive torques or the like of joints of the biped walking robot on the basis of the grasped moments or the like.

As a technique for grasping the floor reaction forces, one disclosed in, for example, Japanese Unexamined Patent Application Publication No. 2000-249570, has been known. According to this technique, a floor reaction force of each leg is grasped as a resultant value (linear combination) of a plurality of trigonometric functions having mutually different cycles of 1/n (n = 1, 2, ...) of a walking cycle, because time-dependent change waveforms of floor reaction forces of each leg periodically change during steady walking of a biped walking body. According to this technique, however, the positions of floor reaction force acting points cannot be grasped, making the technique inadequate for grasping moments acting on the joints of legs of the biped walking mobile body.

There has been also known a technique in which a biped walking mobile body is walked on a force plate installed on a floor so as to grasp floor reaction forces and the positions of floor reaction force acting points on the basis of the outputs of the force plate (refer to, for example, Japanese Unexamined Patent Application Publication No. 2001-29329).

This technique, however, presents a problem in that the floor reaction forces and the positions of floor

reaction force acting points can be grasped only in an environment wherein a force plate is installed, so that the technique cannot be applied to the walking of a biped walking mobile body in a normal environment.

Accordingly, the present applicant has previously proposed in, for example, Japanese Patent Application No. 2002-18798 (Japanese Unexamined Patent Application Publication No. 2003-220584), a technique that permits real-time estimation of the positions of floor reaction force acting points. This technique uses the fact that the inclination angle of a thigh of each leg or the bending angle of a knee joint has a relatively high correlation with the position of a floor reaction force acting point with respect to the ankle of each leg (the positional vector of a floor reaction force acting point, using the ankle as the reference). More specifically, according to the technique, the correlation data (e.g., data tables or arithmetic expressions) showing the correlation between the inclination angles of thighs or the bending angles of knee joints and the positions of floor reaction force acting points is created and stored beforehand, and the positions of floor reaction force acting points are estimated from the correlation data and the inclination angles of thighs or the bending angles of knee joints measured while a biped walking mobile body is walking.

However, further experiment and study by the

inventors of the present application, it has been revealed that the correlation between the inclination angles of thighs or the bending angles of knee joints and the positions of floor reaction force acting points is influenced by the walking speed or the like of a biped walking mobile body and further influenced by the motion modes of a biped walking mobile body, such as a level-ground walking mode, a staircase walking mode, and a slope walking mode. Hence, in order to properly estimate the positions of the floor reaction force acting points by the aforementioned technique, it is necessary to prepare a plurality of types of the above correlation data for each walking speed or motion mode of the biped walking mobile body and to retain them in a memory. This has been inconveniently taking up a major part of the capacity of the memory. There has been another inconvenience in that, when a motion mode is changed over, discontinuity in position of a floor reaction force acting point estimated on the basis of another correlation data before or after the changeover is likely to occur, resulting in a discontinuously changed estimated value of a joint moment when the estimated position of the floor reaction force acting point is used to estimate the joint moment.

The present invention has been made in view of the above background, and it is an object of the present invention to provide a floor reaction force acting point estimating method that makes it possible to grasp, in real

time, the position of a floor reaction force acting point by a relatively simple technique without using a plurality of types of correlation data, and that is particularly suited for grasping the position of a floor reaction force acting point related to a human being as a biped walking mobile body.

Moreover, it is another object of the present invention to provide a method of estimating a joint moment of a biped walking mobile body that makes it possible to grasp, in real time, the moment acting on a joint, such as a knee joint of a leg, by using the aforesaid estimated value of a floor reaction force acting point.

Disclosure of Invention

The findings obtained by great efforts, including a variety of experiments, made by the inventors of the present application, indicate that, when a biped walking mobile body, such as a human being, is walking on a level ground, for example, the horizontal position of the floor reaction force acting point of each leg in contact with the ground is approximately defined by the relative positional relationship among the position of the center of gravity of a biped walking mobile body, the position of the ankle joint of the leg, and the position of the metatarsophalangeal joint of the foot of the leg (the joint of the root of thumb of the foot) rather than by the moving speed or the like of the biped walking mobile body.

To be more specific, depending on whether the position of the center of gravity is behind the position of an ankle joint, before the position of a metatarsophalangeal joint, or between the position of the ankle joint and the position of the metatarsophalangeal joint, as observed in the advancing direction of a biped walking mobile body, the horizontal position of a floor reaction force acting point will be substantially equivalent to the horizontal position of the ankle joint, the horizontal position of the metatarsophalangeal joint, or the horizontal position of the center of gravity, respectively. Accordingly, it is possible to estimate any one of the three positions as the horizontal position of a floor reaction force acting point according to the relative positional relationship among the position of the center of gravity, the position of an ankle joint, and the position of a metatarsophalangeal joint. Further, the vertical position of the floor reaction force acting point of each leg in contact with the ground, especially the vertical position relative to an ankle joint, is defined by the vertical distance from the ankle joint to the ground contact surface of the leg.

Accordingly, to fulfill the objects described above, a method of estimating a floor reaction force acting point of a biped walking mobile body in accordance with the present invention, i.e., a method of successively estimating the position of the floor reaction force acting

point of each leg of a biped walking mobile body, includes a first step for successively grasping the position of the center of gravity of a biped walking mobile body, the position of an ankle joint of each leg, and the position of the metatarsophalangeal joint of the foot of the leg, and for successively grasping the vertical distance from the ankle joint to a ground contact surface of each leg in contact with the ground while the biped walking mobile body is in a motion, including at least level-ground walking. The method further includes a second step for successively estimating the horizontal position of the floor reaction force acting point of each leg in contact with the ground during the motion on the basis of a relative positional relationship among the position of the center of gravity, the position of the ankle joint, and the position of the metatarsophalangeal joint of the leg that have been grasped in the aforesaid first step, and also for successively estimating the vertical position of the floor reaction force acting point of the leg as the position vertically apart downward from the ankle joint by the aforesaid vertical distance from the ankle joint to the ground contact surface of the leg grasped in the first step.

According to the method of estimating a floor reaction force acting point in accordance with the present invention, the position of the center of gravity of a biped walking mobile body, the position of the ankle joint

of each leg, and the position of the metatarsophalangeal joint of the foot of the leg are successively grasped in the first step, thereby estimating one of these positions as the horizontal position of the floor reaction force acting point of each leg in contact with the ground on the basis of the relative positional relationship of the positions. This arrangement allows the horizontal position of a floor reaction force acting point to be estimated without using a data table, or map data or the like. Moreover, the vertical distance from the ankle joint to a ground contact surface (floor surface) of each leg in contact with the ground is successively grasped in the first step, thereby estimating the position vertically apart downward from the ankle joint by that vertical distance as the vertical position of the floor reaction force acting point. This arrangement allows the vertical position of a floor reaction force acting point to be estimated without using a data table, or map data or the like.

Thus, according to the method of estimating a floor reaction force acting point in accordance with the present invention, the position of a floor reaction force acting point can be grasped in real time by a relatively simple technique without using a plurality of types of correlation data.

The method of estimating a floor reaction force acting point in accordance with the present invention

makes it possible to grasp the position of the center of gravity, the position of an ankle joint, and the position of a metatarsophalangeal joint by detecting, for example, the inclination angle of a body by a gyro-sensor or an acceleration sensor and by detecting the bending angle of a joint of each leg by a potentiometer or the like, and then by using the detected inclination angle of the body, the detected bending angle of the joint of the leg, and a rigid link model representing a biped mobile body in the form of a rigid linkage assembly.

According to the method of estimating a floor reaction force acting point in accordance with the present invention, depending on whether the position of the center of gravity is behind the position of an ankle joint, before the position of a metatarsophalangeal joint, or between the position of the ankle joint and the position of the metatarsophalangeal joint, as observed in the advancing direction of a biped walking mobile body, the horizontal position of a floor reaction force acting point will be substantially equivalent to the horizontal position of the ankle joint, the horizontal position of the metatarsophalangeal joint, or the horizontal position of the center of gravity, respectively. Hence, to estimate the horizontal position of the floor reaction force acting point in the second step, for each leg in contact with the ground, if the position of the center of gravity is behind the position of the ankle joint of the

leg when observed in the advancing direction of the biped walking mobile body, then the horizontal position of the ankle joint of the leg may be estimated as the horizontal position of the floor reaction force acting point of the leg. If the position of the center of gravity is before the position of a metatarsophalangeal joint of the leg when observed in the advancing direction of the biped walking mobile body, then the horizontal position of the metatarsophalangeal joint of the leg may be estimated as the horizontal position of the floor reaction force acting point of the leg. Further, if the position of the center of gravity is between the position of the ankle joint of the leg and the position of the metatarsophalangeal joint when observed in the advancing direction of the biped mobile body, then the horizontal position of the center of gravity may be estimated as the horizontal position of the floor reaction force acting point of the leg.

This arrangement makes it possible to estimate the horizontal position of a proper floor reaction force acting point on the basis of three types of relative positional relationship among the position of center of gravity, the position of an ankle joint, and the position of a metatarsophalangeal joint. And in this case, the position of the center of gravity continuously changes before or after the position of an ankle joint or before or after the position of a metatarsophalangeal joint, so that the estimated value of the horizontal position of a

floor reaction force acting point can be also continuously changed.

Furthermore, according to the method of estimating a floor reaction force acting point in accordance with the present invention, as one technique for estimating the vertical position of a floor reaction force acting point, for example, the vertical distance from the ankle joint to a ground contact surface of each leg when the biped walking mobile body in an upright stationary state is measured and retained in a memory beforehand. To grasp the vertical distance from the ankle joint to the ground contact surface of each leg in contact with the ground in the first step, the vertical distance retained in the memory is grasped as the vertical distance from the ankle joint to the ground contact surface of each leg in contact with the ground.

In other words, according to the findings of the inventors of the present application, the vertical distance from an ankle joint to a ground contact surface of a leg in contact with the ground usually does not vary much while a biped walking mobile body is in motion, such as level-ground walking, and it is approximately equal to the vertical distance from the ankle joint to the ground contact surface of each leg while the biped walking mobile body is in the upright stationary state. Hence, the vertical position of a floor reaction force acting point can be easily estimated by measuring and retaining in a

memory beforehand the vertical distance from an ankle joint to a ground contact surface of each leg in the upright stationary state, and by grasping the vertical distance retained in the memory as the vertical distance from the ankle joint to the ground contact surface of the leg in contact with the ground while the biped walking mobile body is in motion.

To estimate the vertical position of a floor reaction force acting point with higher accuracy, the vertical distance from the ankle joint to a ground contact surface of each leg and the vertical distance from the metatarsophalangeal joint to the ground contact surface of the leg while the biped walking mobile body is in an upright stationary state are preferably measured and retained in a memory beforehand as a first basic vertical distance and a second basic vertical distance, respectively. And, when grasping the vertical distance from the ankle joint to the ground contact surface of each leg in contact with the ground in the first step, if the position of the center of gravity is behind the position of the metatarsophalangeal joint of the leg as observed in the advancing direction of the biped walking mobile body, then the first basic vertical distance is preferably grasped as the vertical distance from the ankle joint to the ground contact surface of the leg. Further, if the position of the center of gravity is before the position of the metatarsophalangeal joint of the leg as observed in

the advancing direction of the biped walking mobile body, then preferably, the vertical distance between the ankle joint and the metatarsophalangeal joint of the leg is determined, and then the value obtained by adding the second basic vertical distance to the determined vertical distance is grasped as the vertical distance from the ankle joint to the ground contact surface of the leg.

More specifically, if the position of the center of gravity is behind the position of the metatarsophalangeal joint of a leg when observed in the advancing direction of a biped walking mobile body, then the foot of the leg has at least the bottom surface of its heel in contact with the ground, so that the vertical distance from the ankle joint to the ground contact surface of the leg in contact with the ground while the biped walking mobile body is in motion is substantially equal to the first basic vertical distance. Further, if the position of the center of gravity is before the position of the metatarsophalangeal joint of a leg when observed in the advancing direction of the biped walking mobile body, then the foot of the leg is usually in contact with the ground at a toe portion (a portion in the vicinity of the metatarsophalangeal joint) while its heel is off the ground. In this case, the vertical distance from a foot joint of the leg to the ground contact surface is substantially equal to the value obtained by adding the second basic vertical distance to the vertical distance between the foot joint and the

metatarsophalangeal joint. In this case, the vertical distance between the foot joint and the metatarsophalangeal joint can be determined from the positions of those joints grasped in the first step.

Thus, by grasping the vertical distance from an ankle joint to a ground contact surface of a leg as described above, depending on whether the position of the center of gravity is behind or before the position of a metatarsophalangeal joint of the leg as observed in the advancing direction of a biped walking mobile body, the accuracy of the aforesaid vertical distance to be grasped can be improved. This in turn permits higher accuracy of the estimated values of the vertical positions of floor reaction force acting points.

Furthermore, according to a method of estimating a floor reaction force acting point, the motion mode of a biped walking mobile body is determined while the processing of the first step is being executed when the biped walking mobile body is in a motion, including at least level-ground walking of the biped walking mobile body and walking of the biped walking mobile body on a staircase or a slope, and if the determined motion mode of the biped walking mobile body is the level-ground walking, then the position of the floor reaction force acting point of each leg in contact with the ground is successively estimated by the processing of the second step. Meanwhile, if the determined motion mode of the biped walking mobile

body is the walking on a staircase or a slope, then it is preferable to successively estimate the horizontal position of the metatarsophalangeal joint of each leg as the horizontal position of the floor reaction force acting point of the leg and to successively estimate the position vertically apart downward from an ankle joint by the vertical distance from the ankle joint to the ground contact surface of the leg as the vertical position of the floor reaction force acting point of the leg.

Specifically, according to the findings of the inventors of the present application, when a biped walking mobile body, such as a human being, is walking on a staircase or a slope, the floor reaction force acting point during contact with the ground usually tends to center around a metatarsophalangeal joint substantially all through the in-contact-with-the ground period. Hence, when the motion mode of a biped walking mobile body is the walking on a staircase or a slope, it is preferable to estimate the horizontal position of the metatarsophalangeal joint of the leg in contact with the ground as the horizontal position of a floor reaction force acting point rather than estimating the horizontal position of a floor reaction force acting point on the basis of the relative positional relationship among the position of a center of gravity, the position of an ankle joint, and the position of a metatarsophalangeal joint, as in the case of the level-ground walking. This makes it

possible to properly estimate the horizontal position of a floor reaction force acting point in the walking on a staircase or a slope. In this case, the vertical position of the floor reaction force acting point may be estimated in the same manner as in the case of the level-ground walking.

As described above, in the case where the method of estimating the horizontal position of a floor reaction force acting point is determined according as whether the motion mode is the level-ground walking or the walking on a staircase or a slope, whether the motion mode of the biped walking mobile body is the level-ground walking or the walking on a staircase or a slope can be determined on the basis of at least the vertical distance between the ankle joints of both legs of the biped walking mobile body.

More specifically, in the level-ground walking, the vertical distance between the ankle joints of the two legs when both legs are in contact with the ground (in a double stance state) takes a value in the vicinity of substantially zero, whereas in the walking on a staircase or a slope, the vertical distance between the ankle joints of the two legs when both legs are in contact with the ground (in the double stance state) takes a relatively large value. Hence, based on the vertical distance of the ankle joints of the two legs, it can be properly determined whether the motion mode of a biped walking mobile body is the level-ground walking motion mode or the

motion mode of walking on a staircase or a slope.

Next, a method of estimating a joint moment of a biped walking mobile body in accordance with the present invention is a method of estimating a moment acting on at least one joint of each leg of a biped walking mobile body by using an estimated value of the position of a floor reaction force acting point successively determined by the floor reaction force estimating method according to the present invention described above. And this joint moment estimating method includes a step for successively estimating the floor reaction force of each leg in contact with the ground of the biped walking mobile body by using at least a detection output of an acceleration sensor attached to a body of the biped walking mobile body to detect the acceleration of a predetermined part of the body of the biped walking mobile body and a detection output of a body inclination sensor attached to the body to detect an inclination angle of the body, and a step for successively grasping the inclination angle of each rigid corresponding part of a biped walking mobile body that corresponds to each rigid body of a rigid link model representing the biped walking mobile body in the form of a link assembly of a plurality of rigid bodies, the acceleration of the center of gravity of the rigid corresponding part, and the angular acceleration of the rigid corresponding part by using at least a detection output of the body inclination sensor and a detection

output of an angle sensor attached to a joint to detect the bending angle of the joint of each leg of the biped walking mobile body, wherein the moment acting on at least one joint of each leg of the biped walking mobile body is estimated on the basis of an inverse dynamics model by using an estimated value of the floor reaction force, an estimated value of the position of the floor reaction force acting point, an inclination angle of the aforesaid each rigid corresponding part, an acceleration of the center of gravity of the rigid corresponding part and an angular acceleration of the rigid corresponding part, predetermined weight and size of each rigid corresponding part, a predetermined position of the center of gravity of each rigid corresponding part in the rigid corresponding part, and a predetermined inertial moment of each rigid corresponding part.

According to the joint moment estimating method in accordance with the present invention, although it will be discussed in detail later, successively detecting the acceleration of a predetermined part (e.g., the waist) of a body (torso) of a biped walking mobile body by an acceleration sensor and successively detecting the inclination angle of the body by a body inclination sensor allows the floor reaction force acting on each leg in contact with the ground to be successively estimated by using the detection outputs (detected values). Further, successively detecting the bending angle of a joint of

each leg by an angle sensor in addition to detecting the inclination angle of the body by a body inclination sensor makes it possible to successively grasp the inclination angle (this indicates the mutual posture relationship among rigid corresponding parts) of each rigid corresponding part (thigh, crus, etc.) of a rigid link model representing a biped walking mobile body, the acceleration of the center of gravity of the rigid corresponding part, and the angular acceleration of the rigid corresponding part by using the detection outputs (detected values) of the aforesaid body inclination sensor and the angle sensor. This means that the mutual posture relationship among rigid corresponding parts will be known if the inclination angle of the body and the bending angles of joints of each leg are known, so that the inclination angles of the rigid corresponding parts can be known. Further, the position of the center of gravity of a rigid corresponding part in the rigid corresponding part (the position of the center of gravity of the rigid corresponding part in a coordinate system fixed to each rigid corresponding part) can be determined in advance; therefore, based on this and the mutual posture relationship among the rigid corresponding parts, the position of the center of gravity of each rigid corresponding part (the position relative to a reference point fixed at an arbitrary position (e.g., the waist) of a biped walking mobile body) in the entire biped walking

mobile body (in the entire rigid link model) can be known. And, the acceleration of the center of gravity can be grasped as the second-order differentiation value of the position of the center of gravity of each rigid corresponding part. Further, if the inclination angle of each rigid corresponding part is known, then the angular acceleration of each rigid corresponding part can be grasped as the second-order differentiation value thereof.

Further, when the floor reaction force of a biped walking mobile body has been estimated, and the inclination angle of each rigid corresponding part, the acceleration of the center of gravity of the rigid corresponding part, and the angular acceleration of the rigid corresponding part have been grasped, as described above, these pieces of data and the estimated value of a floor reaction force acting point determined by the aforesaid floor reaction force acting point estimating method, the predetermined weight and size (especially length) of each rigid corresponding part, the predetermined position of the center of gravity of each rigid corresponding part in the rigid corresponding part, and the predetermined inertial moment of each rigid corresponding part are used, so that the moment acting on a knee joint or a hip joint of each leg can be estimated on the basis of a publicly known so-called inverse dynamics model. Briefly speaking, the technique based on the inverse dynamics model uses an equation of motion

related to the translational motion of the center of gravity of each rigid corresponding part of a biped walking mobile body and an equation of motion related to a rotational motion of the rigid corresponding part (e.g., the rotational motion about the center of gravity of the rigid corresponding part) to determine the moments acting on joints of the biped walking mobile body that correspond to the joints of a rigid link model in order from the one closest to a floor reaction force acting point. Although it will be discussed in detail later, if it is assumed that, for example, each leg is a link assembly having a thigh and a crus as rigid corresponding parts, then the force acting on the knee joint of the leg (the joint reaction force) will be known by applying the acceleration of the center of gravity of the crus, the estimated value of the floor reaction force acting on the leg, and the value of the weight of the crus to the equation of motion related to the translational motion of the center of gravity of the crus of each leg. Furthermore, the moment of the knee joint of the leg can be estimated by applying the joint reaction force acting on the knee joint of the leg, angular acceleration of the crus of the leg, the estimated position of the floor reaction force acting point of the leg, the estimated value of the floor reaction force of the leg, the position of the center of gravity of the crus in the crus, the data values related to the size (length) of the crus, the value of the

inertial moment of the crus, and the value of the inclination angle of the crus to an equation of motion related to a rotational motion of the crus.

In addition, the joint reaction force acting on the hip joint of the leg can be determined by applying the acceleration of the center of gravity of the thigh, the joint reaction force acting on the knee joint of the leg, and the value of the weight of the thigh to an equation of motion related to the translational motion of the center of gravity of the thigh of each leg. Further, the moment of the hip joint of the leg can be estimated by applying the joint reaction forces acting on the knee joint and the hip joint, respectively, of the leg, the angular acceleration of the thigh of the leg, the position of the center of gravity of the thigh in the thigh and the data values related to the size (length) of the thigh, the value of the inertial moment of the thigh, and the value of the inclination angle of the thigh to an equation of motion related to the rotational motion of the thigh.

The joint moment estimating method in accordance with the present invention makes it possible to estimate, in real-time, the moment acting on a joint of a leg by relatively simple arithmetic processing by using the position of the floor reaction force acting point estimated according to the floor reaction force acting point estimating method in accordance with the present invention described above so as to estimate the moment

acting on a joint of a leg, thus obviating the need for preparing multiple types of correlation data beforehand or for attaching a relatively large sensor to a biped walking mobile body.

Brief Description of the Drawings

Fig. 1 (a) and Fig. 1 (b) are diagrams for explaining a basic principle of a method of estimating floor reaction forces in an embodiment of the present invention, Fig. 2 is a diagram schematically showing a human being as a bipedal walking mobile body and a construction of an apparatus installed on the human being in an embodiment of the present invention, Fig. 3 is a block diagram for explaining the functions of an arithmetic processing unit installed in the apparatus shown in Fig. 2, and Fig. 4 is a diagram showing a rigid link model used for processing performed by the arithmetic processing unit shown in Fig. 3. Fig. 5 is a diagram for explaining a technique for calculating the position (horizontal position) of a metatarsophalangeal joint in a first embodiment of the present invention and a technique for grasping the distance from an ankle joint to a ground contact surface, Fig. 6 (a) to (c) are diagrams for explaining a technique for estimating the horizontal positions of a floor reaction force acting point in a level-ground walking mode, and Fig. 7 is a diagram for explaining the processing in a joint moment estimating means of the arithmetic processing

unit of Fig. 3. Fig. 8 and Fig. 9 are graphs illustrating the time-dependent changes in the horizontal position and the vertical position, respectively, of the floor reaction force acting point in the level-ground walking mode determined according to the first embodiment of the present invention, Fig. 10 and Fig. 11 are graphs illustrating the time-dependent changes in a knee joint moment and a hip joint moment, respectively, in the level-ground walking mode determined according to the first embodiment of the present invention, Fig. 12 and Fig. 13 are graphs illustrating the time-dependent changes in a knee joint moment and a hip joint moment, respectively, in a staircase descent walking mode determined according to the first embodiment of the present invention, Fig. 14 and Fig. 15 are graphs illustrating the time-dependent changes in a knee joint moment and a hip joint moment, respectively, in a staircase ascent walking mode determined according to the first embodiment of the present invention, Fig. 16 and Fig. 17 are graphs illustrating the time-dependent changes in a knee joint moment and a hip joint moment, respectively, in a sitting-onto-a-chair mode determined according to the first embodiment of the present invention, and Fig. 18 and Fig. 19 are graphs illustrating the time-dependent changes in a knee joint moment and a hip joint moment, respectively, in a sitting-onto-a-chair mode determined according to the first embodiment of the present invention. Fig. 20 is a

diagram for explaining a technique for calculating the position of a metatarsophalangeal joint in a second embodiment of the present invention and a technique for grasping the distance from an ankle joint to a ground contact surface.

Best Mode for Carrying Out the Invention

An embodiment to which a method of estimating a floor reaction force acting point and a method of estimating a joint moment in accordance with the present invention will be explained with reference to the accompanying drawings. First, for the convenience of understanding, the basic concept of the technique for estimating floor reaction forces of a biped walking mobile body in the embodiment of the present invention will be explained with reference to Fig. 1. The motional state of a leg of a biped walking mobile body, e.g., the motional state of a leg in a walking mode, comes in a single stance state in which only one leg 2 (the front leg, as observed in the advancing direction of a biped walking mobile body 1 in the figure) of both legs 2 and 2 of the biped walking mobile body 1 is in contact with the ground, as shown in Fig. 1(a), and a double stance state in which both legs 2 and 2 are in contact with the ground, as shown in Fig. 1(b).

First, in the single stance state, the equation of motion (to be more specific, an equation of motion related to the translational motion of a center of gravity) of the

center of gravity of the biped walking mobile body 1 in an absolute coordinate system fixed to the floor on which the biped walking mobile body moves provides a relational expression in which the product of the acceleration of the center of gravity and the weight of the biped walking mobile body 1 is equal to the resultant force of the gravity acting on the center of gravity (= weight of the biped walking mobile body 1 x acceleration of gravity) and the floor reaction force acting from the floor to the ground contact portion of the leg 2 in contact with the ground. Specifically, as shown in, for example, Fig. 1(a), if the components of an acceleration *a* (vector) of a center of gravity (G0) of the biped walking mobile body 1 in an X-axis direction (the horizontal direction relative to the advancing direction of the biped walking mobile body 1) and in a Z-axis direction (the vertical direction) are denoted by ax and az, respectively, and the components of a floor reaction force F (vector) related to the leg 2 in contact with the ground (the supporting leg 2) in the X-axis direction and the Z-axis direction are denoted by Fx and Fz, respectively, in an absolute coordinate system Cf fixed to a floor A, then the equation of motion of the center of gravity G0 is represented by Equation (1) given below.

$$^{T}(Fx,\ Fz - M \cdot g) = M \cdot {}^{T}(ax,\ az) \quad \ldots\ldots (1)$$

(where M: Weight of the biped walking mobile body 1, g: Acceleration of gravity)

The parenthesized portions $^T(\, , \,)$ on both sides in Equation (1) mean the vectors of two components. In the present description, the notation of $^T(\, , \,)$ will denote a vector.

Thus, if the acceleration $a = {}^T(ax, az)$ of the center of gravity G0 of the biped walking mobile body 1 is grasped, then the estimated value of the floor reaction force $F = {}^T(Fx, Fz)$ can be obtained according to the following Equation (2) by using the acceleration *a*, the value of the weight M of the biped walking mobile body 1, and the value of the acceleration of gravity g.

$$^T(Fx, Fz) = M \cdot {}^T(ax, az - g) \quad \dots\dots (2)$$

In this case, the weight M necessary to obtain the estimated value of the floor reaction force F can be grasped beforehand by measurement or the like. Although it will be discussed in detail hereinafter, the position and the acceleration *a* of the center of gravity G0 can be successively grasped by a publicly known technique or the like by using outputs of sensors, such as a sensor for detecting bending angles (rotational angles) of joints of the biped walking mobile body 1, an acceleration sensor, and a gyro sensor.

An equation of motion of the center of gravity of the biped walking mobile body 1 (specifically, an equation of motion related to the translational motion of the center of gravity) in the state wherein both legs are in contact with the ground provides a relational expression in which

the product of the acceleration of the center of gravity and the weight of the biped walking mobile body 1 is equal to the resultant force of the gravity acting on the center of gravity (= weight of the biped walking mobile body x acceleration of gravity) and the floor reaction forces acting from the floor to the ground contact portion of each of the two legs 2 and 2 (two floor reaction forces associated with the two legs 2 and 2, respectively). Specifically, as shown in, for example, Fig. 1(b), if the XZ coordinate components of a floor reaction force Ff related to the leg 2 at the front side with respect to the advancing direction of the biped walking mobile body 1 are denoted by Ffx and Ffz, and the XZ coordinate components of a floor reaction force Fr related to the leg 2 at the rear side are denoted by Frx and Frz, then the equation of motion of the center of gravity G0 is represented by Equation (3) given below.

$$^{T}(Ffx + Frx,\ Ffz + Frz - M \cdot g) = M \cdot {}^{T}(ax,\ az) \qquad \cdots\cdots (3)$$

The meanings of ax, az, M, and g in Equation (3) are as described above.

Meanwhile, according to the knowledge of the inventors of the present application, the floor reaction forces Ff and Fr related to the legs 2 and 2, respectively, in the double stance state may be considered to act generally toward the center of gravity G0 of the biped walking mobile body 1 from particular parts in the

vicinity of the bottom ends of the legs 2 and 2, e.g., the portions of ankle joints 12f and 12r, as shown in Fig. 1(b). At this time, a certain relational expression holds between the positions of the ankle joints 12f and 12r of the legs 2 and 2 relative to the center of gravity G0 and the floor reaction forces Ff and Fr acting on the legs 2 and 2, that is, a relational expression representing a relationship in which the direction of a segment connecting the center of gravity G0 and the ankle joints 12f and 12r of the legs 2 and 2 (the direction of the positional vectors of the ankle joints 12f and 12r relative to the center of gravity G0) agrees with the direction of the floor reaction forces Ff and Fr related to the legs 2 and 2.

Specifically, referring to Fig. 1(b), if the coordinates of the position of the center of gravity G0 in the absolute coordinate system Cf is denoted by (Xg, Zg), the coordinates of the position of the ankle joint 12f of the leg 2 at the front side is denoted by (Xf, Zf), and the coordinates of the position of the ankle joint 12r of the leg 2 at the rear side is denoted by (Xr, Zr), then the above relational expression will be the following equation (4):

$$(Zf-Zg)/(Xf-Xg)=Ffz/Ffx$$

$$(Zr-Zg)/(Xr-Xg)=Frz/Frx$$

...... (4)

Equation (5) given below is derived from the Equation

(4) and the above Equation (3):

$$Ffx = M \cdot \{\Delta Xf \cdot (\Delta Zr \cdot ax - \Delta Xr \cdot az - \Delta Xr \cdot g)\} / (\Delta Xf \cdot \Delta Zr - \Delta Xr \cdot \Delta Zf)$$
$$Ffz = M \cdot \{\Delta Zf \cdot (\Delta Zr \cdot ax - \Delta Xr \cdot az - \Delta Xr \cdot g)\} / (\Delta Xf \cdot \Delta Zr - \Delta Xr \cdot \Delta Zf)$$
$$Frx = M \cdot \{\Delta Xr \cdot (-\Delta Zf \cdot ax + \Delta Xf \cdot az + \Delta Xf \cdot g)\} / (\Delta Xf \cdot \Delta Zr - \Delta Xr \cdot \Delta Zf)$$
$$Frz = M \cdot \{\Delta Zr \cdot (-\Delta Zf \cdot ax + \Delta Xf \cdot az + \Delta Xf \cdot g)\} / (\Delta Xf \cdot \Delta Zr - \Delta Xr \cdot \Delta Zf) \quad \cdots\cdots (5)$$

(where $\Delta Xf=Xf-Xg$, $\Delta Zf=Zf-Zg$, $\Delta Xr=Xr-Xg$, $\Delta Zr=Zr-Zg$)

Accordingly, if the acceleration $a = {}^T(ax, az)$ of the center of gravity G0 of the biped walking mobile body 1 is grasped and the positions of the ankle joints 12f, 12r of the legs 2, 2 relative to the center of gravity G0 of the biped walking mobile body 1 (the positions are denoted by ΔXf, ΔZf, ΔXr, and ΔZr in Equation (5)) are grasped, then the estimated values of the floor reaction forces $Ff = {}^T(Ffx, Ffz)$ and $Fr = {}^T(Frx, Frz)$ of each leg 2 can be obtained according to the above Equation (5) by using the acceleration a, the positions of the ankle joints 12f, 12r, the value of the weight M of the biped walking mobile body 1, and the value of the acceleration of gravity g.

In this case, the weight M necessary to obtain the estimated values of the floor reaction forces Ff and Fr can be grasped beforehand by measurement or the like.

Although it will be discussed in detail hereinafter, the acceleration *a* of the center of gravity G0 and the position of the center of gravity G0, and the positions of the ankle joints 12f, 12r relative to the center of gravity G0 can be successively grasped by a publicly known technique or the like by using outputs of sensors, such as a sensor for detecting bending angles (rotational angles) of joints of the biped walking mobile body 1, an acceleration sensor, and a gyro sensor.

The embodiments (first and second embodiments) explained below are adapted to estimate the floor reaction force acting point and joint moments of each leg 2 while estimating the floor reaction force of each leg 2 at the same time on the basis of the matters explained above.

The first embodiment in which the present invention has been applied to a human being as a biped walking mobile body will now be explained in detail.

As schematically shown in Fig. 2, a human being 1 is roughly constructed of a pair of right and left legs 2, 2, a torso 5 composed of a waist 3 and a chest 4, a head 6, and a pair of right and left arms 7, 7. In the torso 5, the waist 3 is connected to the legs 2, 2 through the intermediary of a pair of right and left hip joints 8, 8, and is supported on the two legs 2, 2. The chest 4 of the torso 5 exists above the waist 3 such that it can be tilted toward the front of the human being 1 with respect to the waist 3. And the arms 7, 7 are provided such that

they extend from right and left sides of the upper part of the chest 4, and the head 6 is supported on the upper end of the chest 4.

Each leg 2 has a thigh 9 extending from the hip joint 8 and a crus 11 extending from the distal end of the thigh 9 through the intermediary of a knee joint 10, a foot 13 being connected to the distal end of the crus 11 through the intermediary of an ankle joint 12.

In the present embodiment, an apparatus described below is attached to the human being 1 to estimate the floor reaction force acting on each leg 2 of the human being 1 that has such a construction, and the acting point thereof, and also to estimate the moments acting on the knee joints 10 and the hip joints 8.

More specifically, attached to the chest 4 of the torso 5 are a gyro sensor 14 that generates outputs based on angular velocities involved in inclinations of the chest 4 (hereinafter referred to as "the chest gyro sensor 14"), an acceleration sensor 15 that generates outputs based on longitudinal accelerations of the chest 4 (hereinafter referred to as "the chest longitudinal acceleration sensor 15"), an arithmetic processing unit 16 constructed of a CPU, a RAM, a ROM, etc., and a battery 17 that provides a power supply of the arithmetic processing unit 16, etc. These chest gyro sensor 14, the chest longitudinal acceleration sensor 15, the arithmetic processing unit 16, and the battery 17 are accommodated in

a shoulder-bag type housing member 18 secured to, for example, the chest 4 through a belt or the like, which is not shown, and are integrally secured to the chest 4 through the intermediary of the housing member 18.

More technically, the acceleration indicated by an output of the chest longitudinal acceleration sensor 15 is the longitudinal acceleration in the direction of a horizontal section of the chest 4 (the direction orthogonal to the axis of the chest 4), and it is the acceleration in the longitudinal horizontal direction (in the direction of the X-axis of the absolute coordinate system Cf of Fig. 2) in a state wherein the human being 1 is standing upright on a level ground, while in a state wherein the waist 3 or the chest 4 is inclined from the vertical direction (the direction of the Z-axis of the absolute coordinate system Cf of Fig. 2), it is the acceleration in the direction inclined relative to the horizontal direction by an inclination angle relative to the vertical direction of the chest 4.

Further, a gyro sensor 19 that generates outputs based on angular velocities involved in inclinations of the waist 3 (hereinafter referred to as "the waist gyro sensor 19"), an acceleration sensor 20 that generates outputs based on longitudinal accelerations of the waist 3 (hereinafter referred to as "the waist longitudinal acceleration sensor 20"), and an acceleration sensor 21 that generates outputs based on vertical accelerations of

the waist 3 (hereinafter referred to as "the waist vertical acceleration sensor 21") are integrally mounted and secured to the waist 3 of the torso 5 through the intermediary of a securing means, such as a belt, which is not shown.

More technically, the waist longitudinal acceleration sensor 20 is a sensor that detects the longitudinal accelerations in the direction of a horizontal section of the waist 3 (the direction orthogonal to the axis of the waist 3), as in the case of the chest longitudinal acceleration sensor 15. More technically, the waist vertical acceleration sensor 21 is a sensor that detects vertical accelerations in the axial direction of the waist 3 (this is orthogonal to the accelerations detected by the waist longitudinal acceleration sensor 20). The waist longitudinal acceleration sensor 20 and the waist vertical acceleration sensor 21 may be integrally constructed by a biaxial acceleration sensor.

Further, attached to the hip joint 8 and the knee joint 10 of each leg 2 are a hip joint angle sensor 22 and a knee joint angle sensor 23 that generate outputs based on bending angles $\Delta\theta c$ and $\Delta\theta d$, respectively, of the hip joint 8 and the knee joint 10. Regarding the hip joint angle sensor 22, Fig. 2 shows only the hip joint angle sensor 22 related to the hip joint 8 of the leg 2 on the front side (on the right side, facing the front of the human being 1); however, another hip joint angle sensor 22

is attached concentrically with the hip joint angle sensor 22 on the front side to the hip joint 8 of the leg 2 on the other side (on the left side, facing the front of the human being 1).

These angle sensors 22 and 23 are composed of, for example, potentiometers, and mounted on each leg 2 through the intermediary of a means, such as a band member, which is not shown. In the example of the present embodiment, the bending angle $\Delta\theta c$ detected by each hip joint angle sensor 22 is, more technically, the rotational angle about the hip joint 8 of the thigh 9 of each leg 2 with respect to the waist 3 (about the axis of the hip joint 8 in the lateral direction of the human being 1), this being based on when the posture relationship between the waist 3 and the thigh 9 of each leg 2 indicates a predetermined posture relationship (e.g., the posture relationship in which the axis of the waist 3 and the axis of the thigh 9 are substantially parallel, as in the state wherein the human being 1 is upright and stationary). Similarly, the bending angle $\Delta\theta d$ detected by each knee joint angle sensor 23 is the rotational angle about the knee joint 10 of the crus 11 relative to the thigh 9 (about the axis of the knee joint 10 in the lateral direction of the human being 1), this being based on when the posture relationship between the thigh 9 and the crus 11 of each leg 2 indicates a predetermined posture relationship (e.g., the posture relationship in which the axis of the thigh 9 and

the axis of the crus 11 are substantially parallel). The axis of the thigh 9 is a straight line connecting the center of the joint (hip joint 8) at one end of the thigh 9 and the center of the joint (knee joint 10) at the other end thereof. Similarly, the axis of the crus 11 is the straight line connecting the centers of the joints (the knee joint 10 and the ankle joint 12) at both ends thereof.

The aforesaid sensors 14, 15, and 19 to 23 are connected to the arithmetic processing unit 16 through the intermediary of signal lines, which are not shown, so as to supply the outputs thereof to the arithmetic processing unit 16. In association with the joint moment estimating method in accordance with the present invention, the sensors 14, 15, 19 and 20 mean body inclination sensors for detecting the inclination angles of the body of the human being 1 as a biped walking mobile body, and the sensors 20 and 21 mean sensors for detecting the accelerations of the waist 3 as a particular part of the human being 1 (the biped walking mobile body).

In Fig. 2, the components marked with parenthesized reference numerals 24 are ankle joint angle sensors that output signals based on the bending angles of the ankle joint 12 of each leg 2, and are related to the second embodiment, which will be discussed later. In the present embodiment (the first embodiment), the ankle joint angle sensors 24 are unnecessary and not actually provided.

The arithmetic processing unit 16 is equipped with

the functional means shown in Fig. 3. In Fig. 3, the parenthesized portion (the portion of the ankle joint angle sensor 24) and the portion enclosed by the chain double-dashed line are related to the second embodiment to be discussed later, and these parenthesized portion and the portion enclosed by the chain double-dashed line are unnecessary. Therefore, in the following explanation of the arithmetic processing unit 16 in the present embodiment, nothing related to these parenthesized portion and the portion enclosed by the chain double-dashed line will be referred to.

As shown in Fig. 3, the arithmetic processing unit 16 in the present embodiment is equipped with a leg motion determining means 25 that uses the detection data of the waist vertical acceleration sensor 21 and the data on an estimated value of a floor reaction force of each leg 2 determined by a floor reaction force estimating means 38, which will be discussed hereinafter, so as to determine whether the motion states of the legs 2, 2 of the human being 1 are in the single stance state (the state shown in Fig. 1 (a)) or the double stance state (the state shown in Fig. 1 (b)). The arithmetic processing unit 16 is further provided with a chest inclination angle measuring means 26 that uses the detection data of the chest longitudinal acceleration sensor 15 and the chest gyro sensor 14 thereby to measure an inclination angle θa in an absolute coordinate system Cf of the chest 4 (specifically, the

inclination angle θa with respect to a vertical direction: refer to Fig. 2) and a waist inclination angle measuring means 27 that uses the detection data of the waist longitudinal acceleration sensor 20 and the waist gyro sensor 19 so as to measure an inclination angle θb in an absolute coordinate system Cf of the waist 3 (specifically, the inclination angle θb relative to a vertical direction: refer to Fig. 2).

The arithmetic processing unit 16 is further provided with a reference acceleration measuring means 28 that uses the detection data of the waist longitudinal acceleration sensor 20 and the waist vertical acceleration sensor 21 and the data of the inclination angle θb of the waist 3 measured by the waist inclination angle measuring means 27 so as to determine an acceleration (translational acceleration) $a_0={}^T(a_{0x}, a_{0z})$ in the absolute coordinate system Cf at an origin O of a bodily coordinate system Cp (the xz-coordinate system in Fig. 2) set at the waist 3, as shown in Fig. 2, as the reference point of the human being 1 in the present embodiment. Here, the bodily coordinate system Cp is, to be more specific, a coordinate system, for example, that has a midpoint of a line connecting centers of the right and left hip joints 8, 8 of the human being 1 defined as the origin O, a vertical direction being defined as a z-axis direction, and a forward horizontal direction of the human being 1 defined as an x-axis direction. The directions of the three axes

are the same as those in the aforesaid absolute coordinate system Cf).

The arithmetic processing unit 16 is further provided with a leg posture calculating means 29 that uses detection data of the hip joint angle sensor 22 and the knee joint angle sensor 23 of each leg 2 and the data of the inclination angle θb of the waist 3 by the waist inclination angle measuring means 27 thereby to determine inclination angles θc and θd of the thigh 9 and the crus 11, respectively, of each leg 2 in an absolute coordinate system Cf (to be specific, inclination angles θc and θd relative to a vertical direction: refer to Fig. 2).

The arithmetic processing unit 16 is further provided with a means 30 for calculating the position of the center of gravity of each portion by using data of an inclination angle θa of the chest 4, an inclination angle θb of the waist 3, and an inclination angle θc of the thigh 9 and an inclination angle θd of the crus 11 of each leg 2, which are obtained by the chest inclination angle measuring means 26, the waist inclination angle measuring means 27, and the leg posture calculating means 29, to determine the position of the center of gravity of each rigid corresponding part of the human being 1 associated with a rigid link model to be discussed hereinafter (specifically, the position of the center of gravity of each rigid corresponding part in the bodily coordinate system Cp), a bodily center of gravity position calculating means 31

that uses the data of the position of the center of gravity of the aforesaid rigid corresponding part so as to determine the position of the center of gravity of the entire human being 1 in the bodily coordinate system Cp, an ankle position calculating means 32 that uses the data of the inclination angles θc and θd of each of the thigh 9 and the crus 11 of each leg 2 obtained by the leg posture calculating means 29 so as to determine the position of the ankle joint 12 of each leg 2 in the bodily coordinate system Cp, and further uses the data of the position of the center of gravity G0 of the entire human being 1 (refer to Fig. 1: hereinafter referred to as "the bodily center of gravity G0") obtained by the bodily center of gravity position calculating means 31 to determine the position of the ankle joint 12 of the leg 2 relative to the bodily center of gravity G0 (specifically, ΔXf, ΔZf, ΔXr and ΔZr in the above Equation (5)), an MP position calculating means 33 that uses the data of the position of the ankle joint 12 (the position in the bodily coordinate system Cp) obtained by the ankle position calculating means 32 to determine the position (specifically the position in the x-axis direction) of a metatarsophalangeal joint 13a of the foot 13 of each leg 2 (indicated by a black dot in Fig. 2: hereinafter referred to as "the MP joint 13a") in the bodily coordinate system Cp, and a bodily center of gravity acceleration calculating means 34 that uses the data of the position of the bodily center of

gravity G0 obtained by the bodily center of gravity position calculating means 31 and the data of the acceleration a_0 at the origin O of the bodily coordinate system Cp obtained by the reference acceleration measuring means 28 thereby to determine an acceleration $a={}^T(ax, az)$(refer to Fig. 1) of the bodily center of gravity G0 in the absolute coordinate system Cf.

To be more specific, the MP joint 13a is the joint of the thumb root of the foot 13.

The arithmetic processing unit 16 is further provided with a means 35 for calculating the acceleration of each portion of a leg by using the data of the position of the center of gravity of each rigid corresponding part of the human being 1 (specifically, the position of the center of gravity of a rigid corresponding part related to the leg 2) obtained by the means 30 for calculating the position of the center of gravity of each portion and the data of the acceleration a_0 at the origin O of the bodily coordinate system Cp obtained by the reference acceleration measuring means 28 so as to determine the acceleration (translational acceleration) of the center of gravity of the thigh 9 and the crus 11 of each leg 2 in the absolute coordinate system Cf, a means 36 for calculating the angular acceleration of each portion of a leg by using the data of the inclination angles θc and θd of the thigh 9 and the crus 11 of each leg 2 by the leg posture calculating means 29 to determine the angular

accelerations of the thigh 9 and the crus 11 of the legs 2, 2 in the absolute coordinate system Cf, a motion mode determining means 37 for determining the motion mode of the human being 1 on the basis of the data of the positions of the ankle joint 12 of each leg 2 in the bodily coordinate system Cp determined by the ankle position calculating means 32 and the data of a determination result of the leg motion determining means 25, and a floor reaction force acting point estimating means 38 for estimating the position of the floor reaction force acting point of each leg 2 in contact with the ground on the basis of the bodily center of gravity G0, the positions of the ankle joint 12 and the MP joint 13a (the positions in the bodily coordinate system Cp) determined by the bodily center of gravity position calculating means 31, the ankle position calculating means 32, and the MP position calculating means 33, respectively, and the motion mode determined by the motion mode determining means 37. The motion modes determined by the motion mode determining means 37 in the present embodiment include, for example, a motion mode in which the human being 1 performs level-ground walking, a motion mode in which the human being 1 walks (ascends or descends) a staircase or a slope, and a motion mode in which the human being 1 sits onto a chair or rises from the chair.

The arithmetic processing unit 16 is further provided with a floor reaction force estimating means 39 for

determining the estimated value of a floor reaction force acting on each leg 2 by using the data of the acceleration *a* of the bodily center of gravity determined by the bodily center of gravity acceleration calculating means 34, the data of the position of the ankle joint 12 of each leg 2 relative to the bodily center of gravity G0 determined by the ankle position calculating means 32, and the data of the determination result of the motion state of the leg 2 given by the leg motion determining means 25, and a joint moment estimating means 40 for estimating moments acting on the knee joint 10 and the hip joint 8 of each leg 2 by using this data of the estimated value of the floor reaction force, the data of the accelerations of the centers of gravity of the thigh 9 and the crus 11 of each leg 2 obtained by the means 35 for calculating the acceleration of each portion of a leg, the data of the angular accelerations of the thigh 9 and the crus 11 of each leg 2 obtained by the means 36 for calculating the angular acceleration of each portion of a leg, the data of the estimated position of a floor reaction force acting point obtained by the floor reaction force acting point estimating means 38, and the data of the inclination angles θc and θd of the thigh 9 and the crus 11, respectively, of each leg 2 obtained by the leg posture calculating means 29.

An operation of the present embodiment will be explained in combination with more detailed description of

the processing by each means of the aforementioned arithmetic processing unit 16.

In the present embodiment, when, for example, the human being 1 performs a motion of the legs 2, such as walking, if a power switch, not shown, of the arithmetic processing unit 16 is turned on while both legs 2 and 2 are in contact with a floor (while both feet 13 and 13 are in contact with the ground), then processing is successively carried out by the arithmetic processing unit 16 at a predetermined cycle time, as explained below, thereby successively determining estimated values or the like of floor reaction forces acting on each leg 2.

First, the arithmetic processing unit 16 executes the processing of the leg motion determining means 25. In the processing of the leg motion determining means 25, the detection data of the upward acceleration of the waist 3 obtained by the waist vertical acceleration sensor 21 is compared with a preset, predetermined threshold value for each cycle time described above. If the detected value of the acceleration exceeds the threshold value, then it is determined that the double stance state as shown in Fig. 1(b) has started and the single stance state as shown in Fig. 1(a) has ended. More specifically, while the human being 1 is walking, when the single stance state is switched to the double stance state, the landing of a free leg 2 onto a floor (coming in contact with the ground) generates a relatively large, substantially upward

acceleration (an acceleration that does not occur in a normal single stance state) at the waist 3 near the hip joint 8. For this reason, the leg motion determining means 25 compares the detection data of the upward acceleration of the waist 3 by the waist vertical acceleration sensor 21 with the predetermined threshold value, as described above, so as to determine the start of the double stance state and the end of the single stance state (in other words, the contact of the free leg 2 with the ground).

In the processing of the leg motion determining means 25, of the estimated values of the floor reaction forces Ff and Fr (refer to Fig. 1(b)) acting on the two legs 2 and 2, respectively, determined by the floor reaction force estimating means 39 in the double stance state, as will be discussed later, the estimated value of the floor reaction force related to the leg 2 at the rear side with respect to the advancing direction of the human being $Fr={}^{T}(Frx, Frz)$(specifically, the absolute value = $\sqrt{(Frx^2+Frz^2)}$ of the floor reaction force Fr determined at the last cycle time of the arithmetic processing unit 16) is compared with a preset, predetermined threshold value (a positive value of substantially "0"). If the absolute value of the estimated value of the floor reaction force Fr drops to the threshold value or less, then it is determined that the double stance state has ended and the single stance state has begun (in other words, the leg 2

at the rear side has left the floor). In the present embodiment, the initial state of the motion state of the leg 2 is the double stance state, and the leg motion determining means 25 determines that the motion state of the leg 2 is the double stance state until the estimated value of the floor reaction force related to one of the legs 2 reduces to the aforesaid threshold value or less.

Whether it is the double stance state or the single stance state may be determined by attaching a ground contact sensor to the bottom surface (specifically, the sole or the like) of the foot 13 of each leg 2 so as to detect whether the foot 13 of each leg 2 is in contact with the ground by the ground contact sensor. Alternatively, an acceleration sensor may be attached to the crus 11 of each leg 2 to determine whether each leg 2 is in contact with the ground on the basis of detection outputs of the acceleration sensor, or the distance between the crus 11 of each leg 2, and a floor surface may be measured by using an infrared distance measuring sensor or the like to determine whether each leg 2 is in contact with the ground on the basis of the measurement value.

In parallel to the processing of the leg motion determining means 25 as described above, the arithmetic processing unit 16 carries out the processing of the chest inclination angle measuring means 26 and the waist inclination angle measuring means 27. In this case, the processing by the chest inclination angle measuring means

26 successively determines the inclination angle θa of the chest 4 in the absolute coordinate system Cf at each cycle time mentioned above by a publicly known technique based on the so-called Kalman filter processing, using the longitudinal accelerations of the chest 4 received from the chest longitudinal acceleration sensor 15 and the chest gyro sensor 14, and the detection data of an angular velocity of the chest 4. Similarly, the processing by the waist inclination angle measuring means 27 successively determines the inclination angle θb of the waist 3 in the absolute coordinate system Cf by using the Kalman filter processing from the detection data of the longitudinal accelerations of the waist 3 and the angular velocity of the waist 3 received from the waist longitudinal acceleration sensor 20 and the waist gyro sensor 19, respectively. Here, the inclination angles θa and θb of the chest 4 and the waist 3, respectively, in the absolute coordinate system Cf denote inclination angles with respect to, for example, the vertical direction (gravitational direction) in the present embodiment.

The inclination angles of the chest 4 and the waist 3 can be alternatively determined by, for example, integrating the detection data of angular velocities obtained by the gyro sensors 14 and 19. However, performing the Kalman filter processing, as in the present embodiment, allows the inclination angles θa and θb of the chest 4 and the waist 3 to be measured with high accuracy.

Next, the arithmetic processing unit 16 performs processing of the leg posture calculating means 29 and the processing of the reference acceleration measuring means 28.

In the processing implemented by the leg posture calculating means 29, the inclination angles θc and θd (inclination angles with respect to the vertical direction: refer to Fig. 2) of the thigh 9 and the crus 11 of each leg 2 are determined at each cycle time, as described below. The inclination angle θc of the thigh 9 of each leg 2 is calculated according to Equation (6) given below on the basis of the current value of the detection data of the bending angle $\Delta\theta c$ of the hip joint 8 obtained by the hip joint angle sensor 22 attached to the leg 2 and the current value of the inclination angle θb of the waist 3 determined by the waist inclination angle measuring means 27:

$$\theta c = \theta b + \Delta\theta c \quad \ldots\ldots (6)$$

where the inclination angle θb of the waist 3 takes a negative value if the waist 3 inclines with respect to the vertical direction such that an upper end portion of the waist 3 juts out farther to the front side of the human being 1 than a lower end portion thereof; and the bending angle $\Delta\theta c$ of the hip joint 8 takes a positive value if the thigh 9 inclines with respect to the axial center of the waist 3 such that a lower end portion of the thigh 9 juts out toward the front side of the human being 1.

Furthermore, the inclination angle θd of the crus 11 of each leg 2 is calculated according to Equation (7) given below on the basis of the current value of the inclination angle θc of the thigh 9 determined as described above and the current value of the detection data of the bending angle $\Delta\theta d$ of the knee joint 10 obtained by the knee joint angle sensor 23 attached to the leg 2:

$$\theta d = \theta c - \Delta\theta d \quad \ldots\ldots (7)$$

where the bending angle of the knee joint 10 takes a positive value if the crus 11 inclines toward the rear side of the thigh 9 with respect to the axial center of the thigh 9.

In the processing of the reference acceleration measuring means 28, the acceleration $a_0={}^T(a_0x,\ a_0z)$ in the absolute coordinate system Cf of the origin O of the bodily coordinate system Cp is determined as described below. If the current value of the detection data of a longitudinal acceleration of the waist 3 obtained from the waist longitudinal acceleration sensor 20 is denoted by a_p, and the current value of the detection data of the vertical acceleration of the waist 3 obtained from the waist vertical acceleration sensor 21 is denoted by a_q, then the acceleration $a_0={}^T(a_0x,\ a_0z)$ in the absolute coordinate system Cf is determined according to expression (8) given below from the detection data a_p and a_q and the current value of the inclination angle θb of the waist 3

obtained by the waist inclination angle measuring means 27:

$$a_0 = {}^T(a_0x,\ a_0z)$$
$$= {}^T(a_p \cdot \cos\theta b - a_q \cdot \sin\theta b,\ a_p \cdot \sin\theta b + a_q \cdot \cos\theta b - g) \quad \cdots\cdots (8)$$

The arithmetic processing unit 16 then carries out the processing of the means 30 for calculating the position of the center of gravity of each portion to determine the position of the center of gravity of each rigid corresponding part of the human being 1 in the bodily coordinate system Cp (the position relative to the origin of the bodily coordinate system Cp), using a rigid link model explained below.

As shown in Fig. 4, a rigid link model R used in the present embodiment is a model representing the human being 1 by connecting rigid bodies R1, R1 corresponding to the thighs 9 of the respective legs 2, rigid bodies R2, R2 corresponding to the cruses 11, a rigid body R3 corresponding to the waist 3, and a rigid body R4 corresponding to a portion 38 combining the chest 4, the arms 7, 7, and the head 6 (hereinafter referred to as "the body 38"). In this case, the connection of the respective rigid bodies R1 and the rigid body R3 and the connection of the rigid bodies R1 and the rigid bodies R2 correspond to the hip joints 8 and the knee joints 10, respectively. The connection of the rigid body R3 and the rigid body R4 provides a tilt supporting point 39 of the chest 4 with

respect to the waist 3.

In the present embodiment, the positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts (the thighs 9 and the cruses 11 of the respective legs 2, the waist 3, and the body 38) of the human being 1 associated with the rigid bodies R1 to R4 of the rigid link model R are determined in advance and stored in a memory, not shown, of the arithmetic processing unit 16.

The positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts that have been stored and retained in the arithmetic processing unit 16 are the positions in a coordinate system fixed with respect to the rigid corresponding parts. In this case, as examples of data indicating the positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts, the distances in the axial direction of the rigid corresponding parts from the midpoints of joints at one end of each of the rigid corresponding parts are used. Specifically, for example, the position of the center of gravity G1 of each thigh 9 is indicated as the position at a distance t1 in the axial direction of the thigh 9 from the center of the hip joint 8 of the thigh 9, and the position of the center of gravity G2 of each crus 11 is indicated as the position at a distance t2 in the axial direction of the crus 11 from the center of the knee joint 10 of the crus 11, as shown in Fig. 4. The values

of the distances t1 and t2 are determined beforehand and retained in a memory in the arithmetic processing unit 16. The same applies to the positions of the centers of gravity G3 and G4 of other rigid corresponding parts.

To be more precise, the position of the center of gravity G4 of the body 38 is subject to influences of motions of the arms 7 and 7 included in the body 38. In a walking mode, the arms 7 and 7 are generally positionally symmetrical with respect to the axial center of the chest 4, so that the position of the center of gravity G4 of the body 38 does not change much, and becomes substantially the same as the position of the center of gravity G4 of the body 38 in, for example, an upright stationary state.

According to the present embodiment, in addition to the data indicating the positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts (the thighs 9 and the cruses 11 of the legs 2, the waist 3, and the body 38), the data of weights of the rigid corresponding parts or the data of sizes of the rigid corresponding parts (e.g., data of lengths of the rigid corresponding parts) are determined beforehand and retained in a memory in the arithmetic processing unit 16.

The weight of the crus 11 includes the weight of the foot 13. As described above, the data to be stored and retained in the arithmetic processing unit 16 beforehand may be determined by actual measurement or the like, or may be estimated on the basis of human average statistic

data from height and weight of the human being 1. Generally, the positions of the centers of gravity G1, G2, G3 and G4, the weights and sizes of the rigid corresponding parts are correlated with the height and weight of a human being. Based on the correlation data and from the height and weight of the human being, the positions of the centers of gravity G1, G2, G3 and G4, the weights, and sizes of the rigid corresponding parts can be estimated with relatively high accuracy.

The means 30 for calculating the position of the center of gravity of each portion uses the data stored and retained beforehand in the arithmetic processing unit 16, as described above, the current values of the inclination angle θa of the chest 4 (= the inclination angle of the body 38) and the inclination angle θb of the waist 3 determined by the chest inclination angle measuring means 26 and the waist inclination angle measuring means 27, respectively, and the current values of the inclination angles θc and θd of the thigh 9 and the crus 11 of each leg 2 determined by the leg posture calculating means 29 so as to determine the positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts in the bodily coordinate system Cp (the xz-coordinate system shown in Fig. 4) having the origin O fixed at the waist 3.

In this case, the inclination angles θa to θd of the rigid corresponding parts (the thighs 9 and the cruses 11 of the legs 2, the waist 3, and the body 38) have been

determined, as described above; therefore, the positions and postures of the rigid corresponding parts in the bodily coordinate system Cp are obtained from the data of the inclination angles θa to θd and the data of the sizes of the rigid corresponding parts. Thus, the positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts in the bodily coordinate system Cp can be determined.

Specifically, referring to, for example, Fig. 4, regarding the leg 2 positioned on the left side in Fig. 4, the inclination angle of the thigh 9 in the bodily coordinate system Cp (the inclination angle relative to the z-axis direction) is θc (in this case, $\theta c < 0$ in Fig. 4). Hence, the coordinate of the position of the center of gravity G1 of the thigh 9 in the bodily coordinate system Cp is $(t1 \cdot \sin\theta c, -t1 \cdot \cos\theta c)$. The inclination angle in the bodily coordinate system Cp of the crus 11 is θd ($\theta d<0$ in Fig. 4); therefore, if the length of the thigh 9 is denoted by Lc, then the coordinate of the position of the center of gravity G2 of the crus 11 in the bodily coordinate system Cp will be $(Lc \cdot \sin\theta c+t2 \cdot \sin\theta d, -Lc \cdot \cos\theta c-t2 \cdot \cos\theta d)$. The centers of gravity of the thigh 9 and the crus 11 of the other leg 2, and of the waist 3 and the body 38 are determined in the same manner as described above.

After determining the positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts

in the bodily coordinate system Cp by the means 30 for calculating the position of the center of gravity of each portion, the arithmetic processing unit 16 executes the processing by the bodily center of gravity position calculating means 31 to determine the position (xg, zg) of the bodily center of gravity G0 of the human being 1 in the bodily coordinate system Cp, using the data of the positions of the centers of gravity G1, G2, G3 and G4 of the rigid corresponding parts and the data of the weights of the rigid corresponding parts.

If the position of the center of gravity G3 and the weight of the waist 3 in the bodily coordinate system Cp are denoted by (x3, z3) and m3, respectively, the position of the center of gravity G4 and the weight of the body 38 are denoted by (x4, z4) and m4, respectively, the position of the center of gravity G1 and the weight of the thigh 9 of the leg 2, which is located at left as observed in the advancing direction of the human being 1, are denoted by (x1L, z1L) and m1L, respectively, the position of the center of gravity G2 and the weight of the crus 11 of the leg 2 are denoted by (x2L, z2L) and m2L, respectively, the position of the center of gravity G1 and the weight of the thigh 9 of the leg 2 at right are denoted by (x1R, z1R) and m1R, respectively, the position of the center of gravity G2 and the weight of the crus 11 of the leg 2 are denoted by (x2R, z2R) and m2R, respectively, and the weight of the human being 1 is denoted by M

(=m1L+m2L+m1R+m2R+m3+m4), then the position (xg, zg) of the bodily center of gravity G0 of the human being 1 in the bodily coordinate system Cp will be determined by Equation (9) given below:

$$xg = (m1L \cdot x1L + m1R \cdot x1R + m2L \cdot x2L + m2R \cdot x2R + m3 \cdot x3 + m4 \cdot x4) / M$$

$$zg = (m1L \cdot z1L + m1R \cdot z1R + m2L \cdot z2L + m2R \cdot z2R + m3 \cdot z3 + m4 \cdot z4) / M \quad \ldots\ldots (9)$$

After carrying out the processing of the bodily center of gravity position calculating means 31, the arithmetic processing unit 16 further carries out the processing of the bodily center of gravity acceleration calculating means 34, the processing of the ankle position calculating means 32, and the processing of the MP position calculating means 33.

In this case, in the processing by the bodily center of gravity acceleration calculating means 34, first, the two-level differential value of the position (xg, zg) of the bodily center of gravity G0 in the bodily coordinate system Cp, that is, the acceleration $^T(d^2xg/dt^2,\ d^2zg/dt^2)$ of the bodily center of gravity G0 with respect to the origin 0 of the bodily coordinate system Cp is determined, using the time-series data of the position (xg, zg) of the bodily center of gravity G0 in the bodily coordinate system Cp determined by the bodily center of gravity position calculating means 31 for each cycle time mentioned above. Then, a vector sum of the acceleration

${}^{T}(d^2xg/dt^2, d^2zg/dt^2)$ and the acceleration $a_0={}^{T}(a_0x, a_0z)$ in the absolute coordinate system Cf of the origin O of the bodily coordinate system Cp determined by the reference acceleration measuring means 28 is determined, thereby determining an acceleration $a={}^{T}(ax, az)$ of the bodily center of gravity G0 in the absolute coordinate system Cf.

In the processing of the ankle position calculating means 32, first, the position of the ankle joint 12 of each leg 2 in the bodily coordinate system Cp is determined by the same processing as that of the means 30 for calculating the position of the center of gravity of each portion from the current values of the data of the inclination angles θc and θd of the thigh 9 and the crus 11 of each leg 2 determined by the leg posture calculating means 29, the current value of the data of the inclination angle θb of the waist 3 determined by the waist inclination angle measuring means 27, and the data of the sizes (lengths) of the thigh 9 and the crus 11. Specifically, referring to Fig. 4, regarding the leg 2 located on the left side in Fig. 4, if the length of the crus 11 (the length from the center of the knee joint 10 to the center of the ankle joint 12) is denoted by Ld, then the coordinate (x12, z12) of the position of the ankle joint 12 in the bodily coordinate system Cp will be $(Lc \cdot \sin\theta c + Ld \cdot \sin\theta d, -Lc \cdot \cos\theta c - Ld \cdot \cos\theta d)$(where $\theta c<0$, $\theta d<0$ in Fig. 4). The same applies to the other leg 2.

Furthermore, the positional vector ${}^{T}(x12-xg, z12-zg)$

of the ankle 12 of each leg 2 with respect to the bodily center of gravity G0, that is, ΔXf, ΔZf, ΔXr and ΔZr in the above Equation (5), is determined from the position (x12, z12) in the bodily coordinate system Cp of the ankle joint 12 and the current value of the data of the position (xg, zg) of the bodily center of gravity G0 in the bodily coordinate system Cp determined by the bodily center of gravity position calculating means 31.

In the processing of the MP position calculating means 33, the position of the MP joint 13a (more specifically, the position in the x-axis direction in the bodily coordinate system Cp) is determined as follows. Referring to Fig. 5, in the present embodiment, a distance Δxmp0 in the horizontal direction (the x-axis direction) between the ankle joint 12 and the MP joint 13a in the state wherein the human being 1 is upright stationary (in the state wherein the human being 1 is standing upright on a horizontal floor A, having substantially the entire sole of the foot 14 of each leg 2 in contact with the floor A) is actually measured beforehand and retained in a memory in the arithmetic processing unit 16. The distance Δxmp0 may be actually measured and retained in a memory separately for each leg 2, or it may be actually measured only on one leg 2 and shared for both legs 2 and 2.

In general, the horizontal distance between the ankle joint 12 and the MP joint 13a while the human being 1 is in motion, such as level-ground walking, is approximately

equal to the aforesaid distance Δxmp0 in the upright stationary state of the human being 1. Accordingly, in the present embodiment, the position (the position in the x-axis direction) of the MP joint 13a is determined as the position apart from the ankle joint 12 by the aforesaid Δxmp0 in the x-axis direction. Specifically, the value obtained by adding the distance Δxmp0 to an x-axis coordinate component x12 of the current value of the position (x12, z12) of the ankle joint 12 in the bodily coordinate system Cp obtained by the ankle position calculating means 32 is determined as the position in the x-axis direction of the MP joint 13a in the bodily coordinate system Cp.

Next, the arithmetic processing unit 16 executes the processing of the motion mode determining means 37, the processing of the floor reaction force acting point estimating means 38, and the processing of the floor reaction force estimating means 39. In the processing of the motion mode determining means 37, the motion mode of the human being 1 is determined on the basis of the position of the ankle joint 12 of each leg 2 in the bodily coordinate system Cp calculated as described above by the ankle position calculating means 32, and the result of the determination of a leg motion by the leg motion determining means 25. More specifically, for example, if the vertical distance (the distance in the Z-axis direction) between both ankle joints 12, 12 grasped from

the positions (the positions in the bodily coordinate system Cp) of the individual ankle joints 12, 12 of the two legs 2, 2 calculated by the ankle position calculating means 32 when the start of the double stance state (the end of the single stance state) is detected by the leg motion determining means 25 exceeds a predetermined threshold value, then the motion mode of the human being 1 is determined to be the motion mode in which the human being 1 is walking on a slope or a staircase. Further, if the vertical distance between the two ankle joints 12, 12 at the start of the double stance state is the predetermined threshold value or less, then the motion mode of the human being 1 is determined to be the motion mode in which the human being 1 is performing level-ground walking. Further, if, for example, the vertical distance (the distance in the z-axis direction) between the positions of the two ankle joints 12, 12 in the bodily coordinate system Cp and the origin of the bodily coordinate system Cp (this has been set at the waist 3 as described above) decreases, whereas their horizontal distance (the distance in the x-axis direction) is increasing, while the double stance state is continuously detected by the leg motion determining means 25, then the motion mode of the human being 1 is determined to be the one in which the human being 1 is sitting onto a chair. Conversely, if the vertical distance between the positions of the two ankle joints 12, 12 in the bodily coordinate

system Cp and the origin of the bodily coordinate system Cp increases, whereas their horizontal distance is decreasing, then the motion mode of the human being 1 is determined to be the motion mode in which the human being 1 is rising from the chair.

In the processing of the floor reaction force acting point estimating means 38, the floor reaction force acting point related to each leg 2 in contact with the ground (the point at which all floor reaction force is considered to act on an in-contact-with-the-ground spot of the foot 13) is estimated as described below. First, if the motion mode determined by the motion mode determining means 37 is the level-ground walking motion mode, then the relative positional relationship among the bodily center of gravity G0, the ankle joint 12, and the MP joint 13a (specifically, the relative positional relationship in the x-axis direction of the bodily coordinate system Cp) is determined on each leg 2 in contact with the ground on the basis of the current value of the position (the position in the x-axis direction) of the center of gravity G0 in the bodily coordinate system Cp determined by the bodily center of gravity position calculating means 31, the current value of the position (the position in the x-axis direction) of the ankle joint 12 in the bodily coordinate system Cp determined by the ankle position calculating means 32, and the current value of the position (the position in the x-axis direction) of the MP joint 13a in

the bodily coordinate system Cp determined by the MP position calculating means 33.

And, as shown in Fig. 6(a), if the bodily center of gravity G0 is located behind the ankle joint 12 (if the ankle joint 12 is located before the bodily center of gravity G0), then the position of the ankle joint 12 in the x-axis direction is determined as the position of a floor reaction force acting point in the x-axis direction (the horizontal position in the advancing direction of the human being 1), assuming that the floor reaction force acting point exists vertically right below the ankle joint 12. This means that the state in which the ankle joint 12 of the leg 2 in contact with the ground is located before the bodily center of gravity G0 when the human being 1 is walking on a level ground is usually the state in which the foot 13 of the leg 2 is in contact with the floor A at a spot close to the heel thereof. In this state, the floor reaction force acting point of the leg 2 is located substantially right below the ankle joint 12. Accordingly, in the state wherein the ankle joint 12 is located before the bodily center of gravity G0, as shown in Fig. 6(a), the position in the x-axis direction of the floor reaction force acting point of the leg 2 in contact with the ground as described above is determined. Supplementally, there is a case where the ankle joint 12 is located before the bodily center of gravity G0 while the substantially entire sole of the foot 13 of the leg 2 is in contact with the

ground. In such a case also, the floor reaction force related to the leg 2 is concentrated at a portion close to the heel of the foot 13. Hence, the floor reaction force acting point of the leg 2 is located substantially right below the ankle joint 12.

Fig. 6(a) schematically shows only one leg 2 that is in contact with the ground, the other leg being not shown. This will apply to Figs. 6(b) and 6(c) to be explained below.

As shown in Fig. 6(b), if the bodily center of gravity G0 exists between the MP joint 13a and the ankle joint 12 in the x-axis direction, then it is assumed that the floor reaction force acting point exists right below the bodily center of gravity G0 in the vertical direction, so that the position in the x-axis direction of the bodily center of gravity G0 is determined as the position of the floor reaction force acting point in the x-axis direction. More specifically, when the human being 1 is walking on a level ground, the state wherein the bodily center of gravity G0 in the x-axis direction is positioned between the MP joint 13a and the ankle joint 12 of the leg 2 in contact with the ground is the state wherein substantially entire sole of the foot 13 of the leg 2 is in contact with the floor A. In such a state, the floor reaction force acting point of the leg 2 is located substantially right below the bodily center of gravity G0. Therefore, as shown in Fig. 6(b), in the state wherein the bodily center

of gravity G0 in the x-axis direction is positioned between the MP joint 13a and the ankle joint 12 of the leg 2 in contact with the ground, the position in the x-axis direction of the floor reaction force acting point of the leg 2 in contact with the ground is determined as described above.

Further, as shown in Fig. 6(c), if the bodily center of gravity G0 is located before the MP joint 13a (if the MP joint 13a is located behind the bodily center of gravity G0), then it is assumed that the floor reaction force acting point exists right below the MP joint 13a in the vertical direction, so that the position in the x-axis direction of the MP joint 13a is determined as the position of the floor reaction force acting point in the x-axis direction. More specifically, when the human being 1 is walking on a level ground, the state wherein the MP joint 13a of the leg 2 in contact with the ground is located behind the bodily center of gravity G0 is usually the state wherein the foot 13 of the leg 2 is in contact with the floor A at a spot close to the toe thereof. In such a state, the floor reaction force acting point of the leg 2 is located substantially right below the MP joint 13a. Therefore, as shown in Fig. 6(c), in the state wherein the MP joint 13a is positioned behind the bodily center of gravity G0, the position in the x-axis direction of the floor reaction force acting point of the leg 2 in contact with the ground is determined as described above.

Supplementally, there is a case where the MP joint 13a is located behind the bodily center of gravity G0 while substantially entire sole of the foot 13 of the leg 2 is in contact with the ground. In such a case also, the floor reaction force related to the leg 2 is concentrated at a portion close to the toe of the foot 13; therefore, the floor reaction force acting point of the leg 2 is located substantially right below the MP joint 13a.

In the processing of the floor reaction force acting point estimating means 38 in the present embodiment, the position of the floor reaction force acting point of each leg 2 in the x-axis direction is determined in exactly the same manner as in the case of the motion mode of the level- ground walking discussed above if the motion mode determined by the motion mode determining means 37 is the motion mode of sitting onto a chair or rising from the chair.

Meanwhile, if the motion mode determined by the motion mode determining means 37 is the motion mode of walking on a staircase or a slope, then the floor reaction force estimating means 38 assumes that the floor reaction force acting point exists at the position vertically right below the MP joint 13a independently of the relative positional relationship among the bodily center of gravity G0, the ankle joint 12, and the MP joint 13a, and the position of the MP joint 13a in the x-axis direction is determined as the position of the floor reaction force

acting point in the x-axis direction. More specifically, according to the knowledge of the inventors of the present application, when the human being 1 walks on a staircase or a slope, the floor reaction force acting point of the leg 2 in contact with the ground tends to concentrate near the MP joint 13a during most of the period of ground contact. Hence, if the motion mode of the human being 1 is the motion mode of walking on a staircase or a slope, then the position of the floor reaction force acting point in the x-axis direction is determined as described above.

In the processing of the floor reaction force acting point estimating means 38, the vertical position (the position in the z-axis direction) of the floor reaction force acting point of the leg 2 in contact with the ground is further determined as follows. Regardless of the motion mode of the human being 1 determined by the motion mode determining means 37, first, on each leg 2 in contact with the ground, the distance between the ankle joint 12 of the leg 2 and a ground contact surface (the floor A) is grasped. In this case, according to the present embodiment, a value stored and retained beforehand in the arithmetic processing unit 16 is grasped as the distance between the ankle joint 12 and the ground contact surface (the floor A)(hereinafter referred to as "the distance between the ankle joint and the ground contact surface). To be more specific, referring to Fig. 5, a distance Ha from the center of the ankle joint 12 to the floor A

surface (the ground contact surface) when the human being 1 is in the upright stationary state (hereinafter referred to as "the ankle joint reference height Ha") is actually measured in advance and retained in a memory of the arithmetic processing unit 16. The ankle joint reference height Ha may be actually measured for each leg 2 separately, or only one leg 2 may be actually measured and retained in a memory to be shared for both legs 2. Thus, the ankle joint reference height Ha stored and retained as described above is grasped as the distance between the ankle joint and the ground contact surface.

As discussed above, the distance between the ankle joint and the ground contact surface is grasped, and then the vertical position (the position in the z-axis direction) of a floor reaction force acting point is determined as the position vertically apart downward from the position of the ankle joint 12 by the grasped distance between the ankle joint and the ground contact surface. In other words, the vertical position (the position in the bodily coordinate system Cp) of the floor reaction force acting point is determined as the value obtained by subtracting the distance between the ankle joint and the ground contact surface, which has been grasped as described above, from the value of the z-axis component of the position of the ankle joint 12 (the upward direction being defined as the positive direction of the z-axis), regardless of the motion mode of the human being 1

determined by the motion mode determining means 37.

According to the present embodiment, in order to calculate a joint moment by a joint moment estimating means 40, which will be discussed hereinafter, the position in the bodily coordinate system Cp of the floor reaction force acting point decided as described above (xz-coordinate component) is converted into a position defined using the position of the ankle joint 12 in the bodily coordinate system Cp calculated by the ankle position calculating means 32 as its reference. More specifically, the estimated position of a floor reaction force acting point is determined by conversion into a positional vector based on the position of the ankle joint 12 as the reference (hereinafter referred to as "the floor reaction force acting point vector").

By the processing of the floor reaction force acting point estimating means 38 explained above, the floor reaction force acting point vectors (the positions in the x-axis direction and the z-axis direction) based on the ankle joint 12 are estimated on each leg 2 in contact with the ground.

In the processing of the floor reaction force estimating means 39, if the motion mode of the leg 2 determined at the current cycle time by the leg motion determining means 25 is the single stance state, then the estimated value of the floor reaction force $F={}^{T}(Fx, Fz)$ acting on the leg 2 in contact with the ground is

determined according to the above Equation (2) from the values of the weight M and the gravity acceleration g of the human being 1 (these are stored in the arithmetic processing unit 16 beforehand) and the current value of the acceleration a= ^{T}(ax, az) of the bodily center of gravity G0 in the absolute coordinate system Cf determined by the bodily center of gravity acceleration calculating means 34. In this case, the floor reaction force acting on the leg 2 not in contact with the ground (the free leg 2) is ^{T}(0, 0).

If the motion state of the leg 2 determined at the current cycle time by the leg motion determining means 25 is the double stance state, then the estimated values of the floor reaction forces Ff= ^{T}(Ffx, Ffz) and Fr= ^{T}(Frx, Frz) of the individual legs 2 are determined according to the above Equation (5) from the weight M and the gravity acceleration g of the human being 1, the current value of the acceleration a= ^{T}(ax, az) of the bodily center of gravity G0 in the absolute coordinate system Cf determined by the bodily center of gravity acceleration calculating means 34, and the data of the current values of the positions of the ankle joints 12 of the individual legs 2 relative to the bodily center of gravity G0 determined by the ankle position calculating means 32 (the current values of data of ΔXf, ΔZf, ΔXr, and ΔZr of Equation (5)).

Meanwhile, the arithmetic processing unit 16 carries out the processing of the means 35 for calculating the

acceleration of each portion of a leg and the means 36 for calculating the angular acceleration of each portion of a leg in parallel to the processing of the bodily center of gravity position calculating means 31, the bodily center of gravity acceleration calculating means 34, the ankle position calculating means 32, the MP position calculating means 33, the motion mode determining means 37, the floor reaction force acting point estimating means 38, and the floor reaction force estimating means 39 described above.

In this case, in the processing of the means 35 for calculating the acceleration of each portion of a leg, as in the processing of the bodily center of gravity acceleration calculating means 34, first, the two-level differential values of the positions of the centers of gravity G1 and G2 of the thigh 9 and the crus 11 in the bodily coordinate system Cp, that is, the accelerations of the centers of gravity G1 and G2 of the thigh 9 and the crus 11 in the bodily coordinate system Cp (the accelerations relative to the origin 0 of the bodily coordinate system Cp), are determined, using the time-series data of the positions of the centers of gravity G1 and G2 of the thigh 9 and the crus 11, which are rigid corresponding parts of the legs 2 in the bodily coordinate system Cp determined by the means 30 for calculating the position of the center of gravity of each portion at each cycle time. Then, the vector sum of the aforesaid accelerations and the acceleration $a_0={}^T(a_0x, a_0z)$ in the

absolute coordinate system Cf of the waist 3 obtained by the reference acceleration measuring means 28 is determined, thereby determining the accelerations of the thigh 9 and the crus 11, respectively, in the absolute coordinate system Cf (more specifically, the coordinate components of the accelerations in the absolute coordinate system Cf).

In the processing of the means 36 for calculating the angular acceleration of each portion of a leg, the time series data of the inclination angles θc and θd of the thigh 9 and the crus 11 of each leg 2 obtained by the leg posture calculating means 29 for each cycle time is used to determine the two level differential values of the inclination angles θc and θd of the thigh 9 and the crus 11, that is, the angular accelerations of the thigh 9 and the crus 11, respectively.

Next, the arithmetic processing unit 16 executes the processing of the joint moment estimating means 40 to determine the moments acting on the knee joint 10 and the hip joint 8 of each leg 2. This processing is carried out on the basis of a so-called inverse dynamics model by using the current values of the data determined by the floor reaction force estimating means 39, the means 35 for calculating the acceleration of each portion of a leg, the means 36 for calculating the angular acceleration of each portion of a leg, the floor reaction force acting point estimating means 38, and the leg posture calculating means

29, respectively. The inverse dynamics model uses an equation of motion related to a translational motion and the equation of motion related to a rotational motion of each rigid corresponding part of the human being 1 to determine moments acting on joints in order, beginning with a joint closest to a floor reaction force acting point. In the present embodiment, the moments acting on the knee joint 10 and the hip joint 8 of each leg 2 are determined in order.

To be more specific, referring to Fig. 7, first, regarding the crus 11 of each leg 2, the force acting on the ankle joint 12 of the distal portion of the crus 11 (the joint reaction force), the force acting on the portion of the knee joint 10 of the crus 11 (the joint reaction force), and the translational acceleration of the center of gravity G2 of the crus 11 are denoted by ${}^T(F_1x, F_1z)$, ${}^T(F_2x, F_2z)$, and ${}^T(a_2x, a_2z)$, respectively, according to the component notation in the absolute coordinate system Cf, and the weight of the crus 11 is denoted by m_2. At this time, the equation of motion related to the translational motion of the center of gravity G2 of the crus 11 will be the following equation (10):

$${}^T(m_2 \cdot a_2x,\ m_2 \cdot a_2z) = {}^T(F_1x - F_2x,\ F_1z - F_2z - m_2 \cdot g)$$

Therefore,

$${}^T(F_2x,\ F_2z) = {}^T(F_1x - m_2 \cdot a_2x,\ F_1z - m_2 \cdot a_2z - m_2 \cdot g) \quad \text{…… (10)}$$

The acceleration ${}^T(a_2x, a_2z)$ of the center of gravity

G2 of the crus 11 is determined by the means 35 for calculating the acceleration of each portion of a leg. The joint reaction force ${}^T(F_1x, F_1z)$ acting on the ankle joint 12 of the distal portion of the crus 11 is approximately equal to the estimated value of the floor reaction force determined by the floor reaction force estimating means 39 on the leg 2 having the crus 11. To be more specific, in a single stance state, if the leg 2 is in contact with the ground, then the joint reaction force ${}^T(F_1x, F_1z)$ is the floor reaction force ${}^T(Fx, Fz)$ determined by the above Equation (2). If the leg 2 is a free leg, then ${}^T(F_1x, F_1z) = {}^T(0, 0)$. In a double stance state, if the leg 2 is the leg at the rear side relative to the advancing direction of the human being 1, then the joint reaction force ${}^T(F_1x, F_1z)$ is the floor reaction force ${}^T(Frx, Frz)$ of the above Equation (5), whereas if the leg 2 is at the front side, then it is the floor reaction force ${}^T(Ffx, Ffz)$ of the above Equation (5).

Thus, the joint reaction force ${}^T(F_2x, F_2z)$ acting on the knee joint 10 of each leg 2 is determined according to the above Equation (10) from the data of the acceleration ${}^T(a_2x, a_2z)$ of the center of gravity G2 of the crus 11 determined by the means 35 for calculating the acceleration of each portion of a leg, the data of the floor reaction force $(={}^T(F_1x, F_1z))$ determined by the floor reaction force estimating means 39, the data of the weight m_2 of the crus 11 determined in advance, and the value of

the gravity acceleration g.

Referring to Fig. 7, the moment acting on the ankle joint 12 of the distal portion of the crus 11 is denoted by M_1, the moment acting on the portion of the knee joint 10 of the crus 11 is denoted by M_2, the inertial moment about the center of gravity G2 of the crus 11 is denoted by I_{G2}, and the angular acceleration about the center of gravity G2 of the crus 11 is denoted by α_2. In association with Fig. 4 mentioned above, if the distance between the center of gravity G2 of the crus 11 and the center of the knee joint 10 is denoted by t2, and the distance between the center of gravity G2 of the crus 11 and the ankle 12 is denoted by t2′ (=Ld-t2), then the equation of motion related to the rotational motion about the center of gravity G2 of the crus 11 will be Equation (11) shown below:

$$I_{G2}\cdot\alpha_2=M_1-M_2+F_1x\cdot t2'\cdot\cos\theta d-F_1z\cdot t2'\cdot\sin\theta d$$
$$+F_2x\cdot t2\cdot\cos\theta d-F_2z\cdot t2\cdot\sin\theta d$$

therefore,

$$M_2=M_1-I_{G2}\cdot\alpha_2+F_1x\cdot t2'\cdot\cos\theta d-F_1z\cdot t2'\cdot\sin\theta d$$
$$+F_2x\cdot t2\cdot\cos\theta d-F_2z\cdot t2\cdot\sin\theta d \quad \cdots\cdots (11)$$

where M_1 in Equation (11) denotes the moment obtained in terms of the outer product (vector product) of the floor reaction force acting point vector determined as described above by the floor reaction force acting point estimating means 38 on the leg 2 having the crus 11

related to Equation (11) and the floor reaction force vector determined by the floor reaction force estimating means 39 on the leg 2. Further, α_2 denotes the angular acceleration of the crus 11 determined by the means 36 for calculating the angular acceleration of each portion of a leg. Further, θd denotes the inclination angle of the crus 11 determined by the leg posture calculating means 29. Further, $^T(F_1x, F_1z)$ denotes the estimated value of a floor reaction force determined by the floor reaction force estimating means 39 as described above. Further, $^T(F_2x, F_2z)$ is determined according to the above Equation (10). Further, the inertial moment I_{G2} is determined beforehand together with the data or the like of the weight m_2 and size of the crus 11 and stored in the arithmetic processing unit 16.

Accordingly, the moment M_2 acting on the knee joint 10 is determined by the above Equation (11) from the data of the estimated value of a floor reaction force obtained by the floor reaction force estimating means 39, the data of the estimated value of a floor reaction force acting point vector obtained by the floor reaction force acting point estimating means 38, the data of the angular acceleration α_2 of the crus 11 obtained by the means 36 for calculating the angular acceleration of each portion of a leg, the data of the inclination angle θd of the crus 11 obtained by the leg posture calculating means 29, the data of the joint reaction force $^T(F_2x, F_2z)$ determined

according to the above Equation (10), and the data of the inertial moment I_{G2}, the size (Ld), and the position (t2) of the center of gravity G2 of the crus 11 determined in advance.

After determining the moment M_2 acting on the portion of the knee joint 10 of the crus 11 as described above, the joint moment estimating means 40 determines the moment acting on the portion of the hip joint 8 of the thigh 9 by the same processing as the calculation processing for the moment M_2. The basic concept of this processing is the same as that of the technique for determining the moment M_2 of the knee joint 10, so that detailed illustration and explanation will be omitted, an outline thereof being given below.

First, the joint reaction force $^T(F_3x, F_3z)$ acting on the portion of the hip joint 8 of the thigh 9 is determined according to the following Equation (12) (equation having the same form as that of the above Equation (10)) based on the equation of motion related to the translational motion of the center of gravity G1 of the thigh 9 (refer to Fig. 4).

$$^T(F_3x,\ F_3z) = {}^T(F_2x - m_1 \cdot a_1x,\ F_2z - m_1 \cdot a_1z - m_1 \cdot g) \qquad \text{...... (12)}$$

where $^T(F_2x, F_2z)$ denotes a joint reaction force of the knee joint 10 determined previously according to the Equation (10). Further, $^T(a_1x, a_1z)$ denotes an acceleration (translational acceleration) in the absolute

coordinate system Cf of the center of gravity G1 of the thigh 9 determined by the means 35 for calculating the acceleration of each portion of a leg. Further, m_1 denotes the weight of the thigh 9 determined in advance, and g denotes a gravitational acceleration.

Subsequently, a moment M_3 acting on the portion of the hip joint 8 of the thigh 9 is determined according to Equation (13) given below (an equation of the same form as that of the above Equation (11)) on the basis of the equation of motion related to a rotational motion about the center of gravity G1 of the thigh 9.

$$M_3=M_2-I_{G1}\cdot\alpha_1+F_2x\cdot t1'\cdot\cos\theta c-F_2z\cdot t1'\cdot\sin\theta c$$
$$+F_3x\cdot t1\cdot\cos\theta c-F_3z\cdot t1\cdot\sin\theta c \quad \cdots\cdots (13)$$

M_2 denotes the moment of the knee joint 10 determined according to the above Equation (11), $^T(F_2x,\ F_2z)$ denotes a joint reaction force of the knee joint 10 determined according to the Equation (10), $^T(F_3x,\ F_3z)$ denotes a joint reaction force of the hip joint 8 determined according to the Equation (12), I_{G1} denotes an inertial moment about the center of gravity G1 of the thigh 9 determined in advance, α_1 denotes an angular acceleration of the thigh 9 determined by the means 36 for calculating the angular acceleration of each portion of a leg, and θc denotes an inclination angle of the thigh 9 determined by the leg posture calculating means 29. Further, t1 denotes the distance from the center of the hip joint 8 to the center

of gravity G1 of the thigh 9 (refer to Fig. 4), and t1' denotes the distance from the center of knee joint 10 to the center of gravity G1 of the thigh 9 (L_c-t1 in Fig. 4), these being decided on the basis of the position of the center of gravity G1 and the size (length) of the thigh 9 determined in advance.

The processing explained above is successively executed at each cycle time of the arithmetic processing unit 16 to estimate, in real-time, the floor reaction force acting on each leg 2 and the moments acting on the knee joint 10 of each leg 2 and the hip joint 8.

Although detailed explanation in the present specification will be omitted, the estimated values of the knee joint 10 and the hip joint 8 that have been determined are used for, e.g., controlling an apparatus that aids the walking of the human being 1 (an apparatus that includes an electric motor or the like capable of imparting auxiliary torque to the knee joint 10 and the hip joint 8).

Examples of the time-dependent changes in the estimated value of the floor reaction force acting point determined by the processing of the arithmetic processing unit 16 described above are indicated by the solid lines in Fig. 8 and Fig. 9. Fig. 8 and Fig. 9 show, with the solid lines, the time-dependent changes in the component in the x-axis direction (the horizontal component in the advancing direction) and the component in the z-axis

direction (the vertical component) of the estimated value of the floor reaction force acting point of a leg 2 from the moment the leg 2 comes in contact with the ground to the moment it leaves the floor when the human being 1 is walking on a level ground at a moving speed of, for example, about 4.5 km/h. In this case, the component in the x-axis direction shown in Fig. 8 has been converted to the absolute coordinate system Cf fixed to the floor A. The component in the z-axis direction shown in Fig. 9 is expressed in terms of the z-axis coordinate value (corresponding to the vertical distance from the center of the hip joint 8 to a floor reaction force acting point) in the bodily coordinate system Cp. Fig. 8 and Fig. 9 also show, with dashed lines, the component in the x-axis direction and the component in the z-axis direction of a floor reaction force acting point actually measured using a force plate or the like. As seen in these Fig. 8 and Fig. 9, the estimated values of the floor reaction force acting points agree with actually measured values with relatively good accuracy.

Regarding the component in the z-axis direction shown in Fig. 9, the difference between the estimated value and the actually measured value exhibits a relatively large increase immediately before the leg 2 leaves the floor. This is because, in the present embodiment, the vertical position (the position in the z-axis direction) of the floor reaction force acting point is determined with a

fixed vertical distance between the ankle joint 12 and the floor reaction force acting point (being equal to the distance Ha between the ankle joint and the ground contact surface in Fig. 5), so that the error of the vertical position of the floor reaction force acting point increases in such a state wherein the heel side of the foot 13 floats from the floor A as in the case of immediately before the leg 2 leaves the floor.

Supplementally to Fig. 8, this figure Fig. 8 also shows the calculated values of the positions in the x-axis direction (the values converted into the absolute coordinate system Cf) of the MP joint 13a, the bodily center of gravity G0, and the ankle joint 12. Since the position of a floor reaction force acting point in the x-axis direction in a level-ground walking mode is estimated as described above, in a period in which the bodily center of gravity G0 is located behind the ankle joint 12 (the period until time t1), the position of the floor reaction force acting point in the x-axis direction agrees with the position of the ankle joint 12 in the x-axis direction. In a period wherein the bodily center of gravity G0 is located between the ankle joint 12 and the MP joint 13a in the x-axis direction (the period from time t1 to t2), the position of the floor reaction force acting point in the x-axis direction agrees with the bodily center of gravity G0 in the x-axis direction. Further, in a period wherein the bodily center of gravity G0 is located before the MP

joint 13a (the period after time t2), the position of the floor reaction force acting point in the x-axis direction agrees with the position of the MP joint 13a in the x-axis direction.

Fig. 10 to Fig. 19 show, with solid lines, the time-dependent changes of the estimated values of the moments of the knee joint 10 and the hip joint 8. Fig. 10 and Fig. 11 show the knee joint moment and the hip joint moment, respectively, determined by the arithmetic processing of the arithmetic processing unit 16 when the human being 1 performs level-ground walking at a moving speed of, for example, about 4.5 km/h. Fig. 12 and Fig. 13 show the knee joint moment and the hip joint moment, respectively, determined when the human being 1 walks down a staircase, and Fig. 14 and Fig. 15 show the knee joint moment and the hip joint moment, respectively, determined when the human being 1 walks up a staircase. Further, Fig. 16 and Fig. 17 show the knee joint moment and the hip joint moment, respectively, determined when the human being 1 sits onto a chair, and Fig. 18 and Fig. 19 show the knee joint moment and the hip joint moment, respectively, determined when the human being 1 rises from the chair. These Fig. 10 through Fig. 19 also indicate, with dashed lines, the moments actually measured using a torque meter or the like. As seen in these Fig. 10 through Fig. 19, the trend of the changes in the estimated values of the moment exhibits good agreement with actually measured values. Thus, it is

understood that the estimated positions of the floor reaction force acting points determined in the present embodiment can be determined with sufficiently proper accuracy in estimating the joint moments of the legs 2.

As explained above, the present embodiment makes it possible to estimate the position of a floor reaction force acting point when the human being 1 is walking on a level ground, a staircase or a slope, or sitting onto a chair or rising from the chair, by a simple technique without using a plurality of types of correlation data or the like to estimate floor reaction force acting points.

A second embodiment of the present invention will now be explained with reference to aforementioned Fig. 2 to Fig. 7 and Fig. 20. The present embodiment differs from the first embodiment only partly in construction and processing; therefore, the constructions or functional parts that are identical to those of the first embodiment will be assigned the same reference numerals and drawings as those of the first embodiment, and the explanation thereof will be omitted.

Referring to Fig. 2, according to the present embodiment, in a human being 1, an ankle joint angle sensor 24 that outputs a signal corresponding to a bending angle $\Delta\theta e$ of an ankle joint 12 is attached to the ankle joint 12 of each leg 2, in addition to the devices explained in the first embodiment. As in the knee joint angle sensor 23 or the like, the ankle angle sensor 24 is

composed of a potentiometer, and secured to the ankle joint 12 through a belt or the like, which is not shown. Further, the ankle joint angle sensor 24 is connected to an arithmetic processing unit 16 through the intermediary of a signal line, which is not shown, to input its outputs to the arithmetic processing unit 16.

Here, the bending angle $\Delta\theta e$ detected by each ankle joint angle sensor 24 denotes the angle formed by the line, which connects the center of the ankle joint 12 and the center of an MP joint 13a of a foot 13 linked to the ankle joint 12, and the axial center of a crus 11.

Referring to Fig. 3, in the arithmetic processing unit 16 in the present embodiment, an output of the above each ankle joint angle sensor 24 is received and supplied to an MP position calculating means 33. Further supplied to the MP position calculating means 33 are the positions of the ankle joint 12 (the positions in the bodily coordinate system Cp) calculated by an ankle position calculating means 32 in the same manner as that in the first embodiment, and also an inclination angle θd of the crus 11 calculated by a leg posture calculating means 29.

The construction except for that explained above is identical to the construction of the first embodiment.

The present embodiment having the construction described above differs from the first embodiment only in the processing of the MP position calculating means 33 and the processing of a floor reaction force acting point

estimating means 38 of the arithmetic processing unit 16. More specifically, the present embodiment is adapted to grasp the position of the MP joint 13a more accurately than the first embodiment so as to achieve higher accuracy of estimating the positions of floor reaction force acting points than in the first embodiment. The following will explain in detail the processing of the MP position calculating means 33 and the processing of the floor reaction force acting point estimating means 38 in the present embodiment.

In the processing of the MP position calculating means 33, the position of the MP joint 13a (more specifically, the positions in the x-axis direction and the z-axis direction in a bodily coordinate system Cp) is determined as follows by using detection data or the like of the ankle joint angle sensor 24 or the like.

Referring to Fig. 20, a segment S connecting the center of the ankle joint 12 and the center of the MP joint 13a (hereinafter referred to as "the foot main line S") is assumed, and the angle formed by the foot main line S with respect to the vertical direction (the z-axis direction) (the inclination angle of the foot main line S) is denoted by θe, and the length of the foot main line S (the distance between the ankle joint 12 and the MP joint 13a) is denoted by Ls. At this time, a distance Δxmp in the horizontal direction (the x-axis direction) and a distance Δzmp in the vertical direction (the z-axis

direction) between the ankle joint 12 and the MP joint 13a, that is, a position ${}^T(\Delta xmp, \Delta zmp)$ of the MP joint 13a relative to the ankle joint 12 is given according to the following Equation (14):

$${}^T(\Delta xmp, \Delta zmp) = (Ls \cdot \sin\theta e, Ls \cdot \cos\theta e) \quad \ldots\ldots (14)$$

In this case, the foot 13 may be regarded as substantially a rigid body, and at this time, Ls takes a constant.

Further, the inclination angle θe of the foot main line S is given according to the following Equation (15), using the bending angle Δθe of the ankle joint 12 detected by the ankle joint angle sensor 24 and the inclination angle θd of the crus 11 determined by the leg posture calculating means 29:

$$\theta e = \theta d - (180 - \Delta\theta e) \quad \ldots\ldots (15)$$

In Equation (15), "degrees" is used as the unit of angles.

In the processing of the MP position calculating means 33, the inclination angle θe of the foot main line S is first determined according to the above Equation (15) from the current value of the data of the inclination angle θd of the crus 11 of each leg 2 determined by the leg posture calculating means 29, and the current value of the detection data of the bending angle Δθe of the ankle joint 12 obtained from the ankle joint angle sensor 24 attached to the leg 2. Then, the position ${}^T(\Delta xmp, \Delta zmp)$

of the MP joint 13a relative to the ankle joint 12 is determined according to the above Equation (14) from the determined inclination angle θe and the length Ls of the foot main line S actually measured beforehand on the human being 1 and stored and retained in the arithmetic processing unit 16. Furthermore, the position of the MP joint 13a in the bodily coordinate system Cp is determined by calculating the vector sum of the position $^T(\Delta xmp, \Delta zmp)$ and the position $^T(x12, z12)$ of the ankle joint 12 determined by the ankle position calculating means 32 (the position in the bodily coordinate system Cp) $^T(x12, z12)$.

In the processing of the floor reaction force acting point estimating means 38, the horizontal position (the position in the x-axis direction) of a floor reaction force acting point of each leg 2 in contact with the ground is determined by the same technique as that in the first embodiment. Therefore, the explanation of the processing for estimating the horizontal positions of floor reaction force acting points will be omitted.

Meanwhile, in the processing of the floor reaction force acting point estimating means 38, the technique for estimating the vertical position (the position in the z-axis direction) of the floor reaction force acting point of each leg 2 in contact with the ground is different from that in the first embodiment; the vertical position of a floor reaction force acting point is decided as follows. Regardless of the motion mode of the human being 1

determined by a motion mode determining means 37, first, on each leg 2 in contact with the ground, the distance between the ankle joint 12 of the leg 2 and the ground contact surface (a floor A), that is, the distance between the ankle joint and the ground contact surface, is grasped. In this case, the method for grasping the distance between an ankle joint and a ground contact surface is decided, depending on whether the bodily center of gravity G0 is located before or behind the MP joint 13a in the x-axis direction. If the bodily center of gravity G0 is located behind the MP joint 13a, then it is generally considered that the bottom of the heel of a foot 13 is substantially in contact with the floor A or is positioned at substantially the same height as the surface of the floor A. In this case, therefore, the aforesaid ankle joint reference height Ha actually measured when the human being 1 is in an upright stationary state and stored and retained beforehand in the arithmetic processing unit 16 (refer to Fig. 5) is grasped as the distance between the ankle joint and the ground contact surface.

If the bodily center of gravity G0 is located before the MP joint 13a, then the heel of the foot 13 is usually floating above the surface of the floor A. In this case, the distance between the ankle joint and the ground contact surface is calculated as follows. Referring to the aforesaid Fig. 20, if the heel of the foot 13 is floating above the surface of the floor A, then the

distance between the ankle joint and the ground contact surface will be the sum of the vertical distance Δzmp between the ankle joint 12 and the MP joint 13a and the distance between the MP joint 13a and the ground contact surface (the surface of the floor A). In this case, the distance between the MP joint 13a and the ground contact surface is substantially identical to a distance Hb between the MP joint 13a and the surface of the floor A (hereinafter referred to as "the MP joint reference height Hb") in a state wherein the human being 1 is standing in an upright posture with substantially the entire sole of the foot 13 in contact with the floor A (in the aforesaid upright stationary state), as shown in Fig. 5. Hence, according to the present embodiment, the MP joint reference height Hb is actually measured together with the ankle joint reference height Ha beforehand and stored and retained in the arithmetic processing unit 16. And, if the bodily center of gravity G0 is located before the MP joint 13a, then the sum of the vertical distance Δzmp between the ankle joint 12 and the MP joint 13a grasped from the positions of these joints in the bodily coordinate system Cp and the MP joint reference height Hb is determined as the distance between the ankle joint and the ground contact surface.

The MP joint reference height Hb may be actually measured and stored and retained for each foot 13, or the actually measured value of only one foot 13 may be shared

for both feet 13 and 13. In correspondence to the floor reaction force acting point estimating method in accordance with the present invention, the ankle joint reference height Ha and the MP joint reference height Hb correspond to a first basic vertical distance and a second basic vertical distance, respectively.

After the distance between the ankle joint and the ground contact surface is grasped, the vertical position (the position in the z-axis direction) of a floor reaction force acting point is determined as the position vertically apart downward from the position of the ankle joint 12 by the grasped distance between the ankle joint and the ground contact surface in the same manner as that in the first embodiment. In other words, the vertical position (the position in the bodily coordinate system Cp) of the floor reaction force acting point is determined as the value obtained by subtracting the distance between the ankle joint and the ground contact surface, which has been grasped as described above, from the value of the z-axis component of the position of the ankle joint 12 (the upward direction being defined as the positive direction of the z-axis), regardless of the motion mode of the human being 1 determined by a motion mode determining means 37.

In the present embodiment also, as in the first embodiment, in order to calculate a joint moment by a joint moment estimating means 40, the position in the bodily coordinate system Cp of the floor reaction force

acting point decided as described above (xz-coordinate component) is converted into a position defined using the position of the ankle joint 12 in the bodily coordinate system Cp calculated by the ankle position calculating means 32 as its reference.

The processing of the arithmetic processing unit 16 except for the MP position calculating means 33 and the floor reaction force acting point estimating means 38 explained above is the same as that in the first embodiment.

The present embodiment makes it possible to grasp the positions of the MP joint 13a (the positions in the x-axis direction and the z-axis direction) with relatively high accuracy, thus allowing the positions, particularly the vertical positions, of floor reaction force acting points to be estimated with higher accuracy than that in the first embodiment. Moreover, the joint moments acting on the knee joint 10 and the hip joint 8 can be estimated also with higher accuracy than that in the first embodiment.

The distance between an ankle joint and a ground contact surface determined to estimate the vertical position of a floor reaction force acting point can be determined by a technique other than the techniques explained in the first embodiment and the second embodiment. For example, an optical distance measuring sensor, such as an infrared distance measuring sensor, is

attached to an appropriate portion of the crus 11 of each leg 2 (specifically, the portion apart from the ankle joint 12 toward the knee joint 10 by a predetermined distance in the axial direction of the crus 11), and the distance in the axial direction of the crus 11 between the portion to which the distance measuring sensor has been attached and a floor surface (the ground contact surface of the leg 2) is measured. Then, from the measured distance and the inclination angle θd of the crus 11, the vertical distance between the portion equipped with the distance measuring sensor and the floor surface (hereinafter referred to as "the distance between the sensor and the floor surface") is calculated by geometric computation (trigonometric function computation). Further, from the distance between the portion equipped with the distance measuring sensor and the ankle joint 12 (a fixed value) and the inclination angle θd of the crus 11, the vertical distance between the portion and the ankle joint 12 is determined by the trigonometric function computation, and then the determined vertical distance is subtracted from the aforesaid distance between the sensor and the floor surface so as to determine the distance between the ankle joint and the ground contact surface. Thus, determining the distance between the ankle joint and the ground contact surface makes it possible to accurately estimate the vertical position of a floor reaction force acting point without using the ankle joint angle sensor 24.

In this case, the horizontal position of a floor reaction force acting point may be estimated using the same technique as that of the first embodiment.

In the embodiments explained above, the examples, in which the present invention has been applied to the human being 1, have been explained; however, the present invention can be applied also to a biped walking robot as a biped walking mobile body.

Industrial Applicability

As is obvious from the above explanation, the present invention makes it possible to estimate a joint moment of a leg of a biped walking mobile body, such as a human being, so that the estimated joint moment can be applied for controlling the operation of a walking aid apparatus or the like that aids the walking of a human being. For example, a part of the estimated joint moment may be generated by the walking aid apparatus so as to conduct control for reducing load on the human being.